Sensors and Sensor Systems Research and Development at APL with a View Toward the Future

Joseph J. Suter

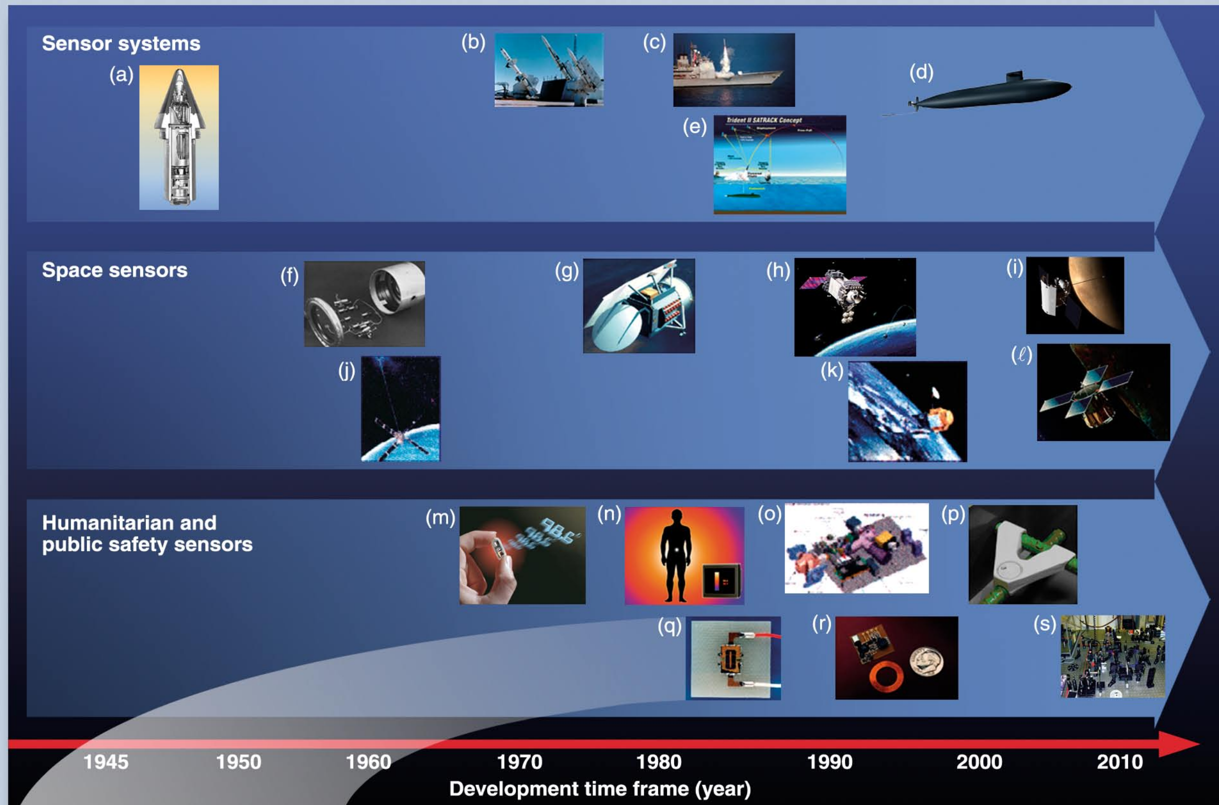
Sensor development continues to be an area of science and technology with great growth potential for innovation at APL. During the Laboratory's 60-year history, many APL-developed sensors and sensor systems have made critical contributions to the exploration of space, military missions, and humanitarian needs. Recent development trends in sensor technologies show that future sensors will be part of autonomous sensor networks that are web-based and fully integrated into an end system or product. These sensor systems will be highly miniaturized and operate as part of a network using the information technology and communication systems of tomorrow.

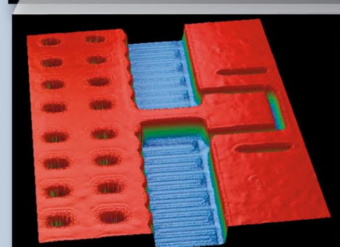
BACKGROUND: 1942–PRESENT

Over the past six decades APL has developed many sensors and sensor systems for underwater, terrestrial, and space applications.[1] Sensor R&D started in the early 1940s with the VT fuze and evolved into innovative sensor systems such as underwater acoustic arrays, biochemical mass spectrometers, space instruments, and telemetric ingestible sensors.[2–4] Many of these major sensors and sensor systems have found practical applications in DoD systems, NASA/DoD satellites, and public safety systems and are displayed on the following page.[1–13] For example, more than 130 APL-developed sensors have flown on NASA and DoD space missions (R. McNutt, APL, private communication, 2004). The Laboratory's Midcourse Space Experiment (MSX), sponsored by the Ballistic Missile Defense Organization, successfully demonstrated the detection of missile launches from space using the visible, UV, and IR spectral ranges.[6] The recently launched MESSENGER spacecraft contains a suite of instruments for exploration of the planet Mercury in 2011.[7] In addition, TOPEX, with radar altimeters developed by APL and the Centre National d'Etudes Spatiales, has been credited with discovering the El Niño effect.[8] The Laboratory also developed the first ingestible telemetric sensor that could measure a patient's core body temperature. Work on this sensor began in the early 1980s and resulted in a commercial product.[10]

As part of the Bird-Borne and the Remote Environmental Sensing Technology programs, APL devised the first miniature satellite transmitter for tracking migratory birds.[14] Twenty years ago, the U.S. Army initiated this effort at APL to develop small transmitters and sensor systems to track birds using the French–U.S. Argos–Tiros satellite system. These transmitters linked with various sensors (acoustic, temperature, barometer, pressure) to collect information on the birds' environment as well as their behavior. Early versions of these

HISTORICAL OVERVIEW OF SELECTED SENSORS AND SENSOR SYSTEMS DEVELOPED BY APL





Over its 60-year history APL has made significant contributions to the development of sensor systems, space sensors, and humanitarian and public safety sensors. Some of these developments, many of which are still operational, are highlighted here. (a) VT fuze. Variable-Time fuze capable of detecting the presence of enemy aircraft and then detonating at the instant of optimal damage to the aircraft (1941–1945).[1] (b) Typhon AN/SPG 59. Multifunction radar developed during the mid-1950s and early 1960s. Capable of scanning a field of view of 360° every second and tracking 10 targets at intervals of less than 1/10th of a second (1968–1973).[1] (c) Aegis Weapon System. Designed for automatic sequencing from target detection to the kill event.[1] (d) Trident Sonar Evaluation Program. APL designed complex array sensors to study the physics of submarine detection in the ocean environment. The program includes the design of sensors and measuring systems as well as data analysis and modeling (1970–present).[5] (e) SATRACK. Satellite navigation technology for tracking a missile in flight with extreme accuracy. Capable of measuring the position of missiles to within a few feet (late 1970s–late 1980s).[1] (f) DISCOS. Disturbance Compensation System developed jointly by APL and Stanford University. First satellite that could move in a drag-free environment using an innovative free-floating sphere sensor and compensation system (late 1970s).[1] (g) Geosat. Satellite built for the Navy. Its radar altimeter was able to measure the height of the ocean surface to within centimeters (1985).[1] (h) MSX. Midcourse Space Experiment, a multi-optical sensor satellite, demonstrated the capability of tracking incoming ballistic missiles (1993–present).[6] (i) MESSENGER. Carries seven sensors. Scheduled to explore the planet Mercury in late 2011.[7] (j) TRANSIT. Navigation system invented by APL and considered to be the predecessor of today's GPS (1956–1980).[1] (k) TOPEX. NASA-sponsored effort with a joint development team including APL, Caltech JPL, and Centre National d'Etudes Spatiales in France. The TOPEX satellite's altimeters discovered the El Niño oceanographic phenomenon in the Pacific Ocean (1992–present).[8] (l) NEAR. Near Earth Asteroid Rendezvous imaged a near-Earth asteroid using an APL-developed laser altimeter and set a first by landing on the asteroid (1996).[9] (m) Ingestible pill. Innovative quartz crystal sensor capable of measuring a patient's core body temperature (late 1980s).[10] (n) PIMS. Programmable Implantable Medication System. Developed by APL and the JHU School of Medicine (late 1970s–early 1980s).[10] (o) Time-of-Flight (TOF) Mass Spectrometer. The first fully operational hand-carried system using TOF mass spectroscopy to detect chemical agents (1993–present).[11,12] (p) Embedded aggregate sensor. The sensor is placed inside poured concrete and measures the effects of corrosion on the rebar used as reinforcement (1999–present).[4] (q) Xylophone magnetometer. Novel MEMS-based magnetometer having greater dynamic range and resolution than fluxgate magnetometers (late 1990s–present).[2] (r) Prototype embedded strain gauge sensor. Developed for potential use as a microsensor to measure strains in composite materials (1999).[13] (s) Terahertz (10^{12}–10^{14} Hz, also called the very long wavelength IR region) mine detector. Emerging sensor for potential detection of plastic mines (1997–present).[4]

transmitters and sensors, which were placed on eagles, yielded important information on their migration, nesting, and wintering habits. These early bird-borne sensor platforms formed the foundation for APL's entry into the field of tagging, tracking, and locating (TTL). Recent TTL devices using refined Doppler positioning systems incorporate unattended sensors and miniature communications systems.

As part of our service to the nation, APL was tasked in the late 1950s to participate in developing a missile system—Typhon—that incorporated a multifunction radar system.[1] The radar used an innovative set of microwave radar lenses that, in combination with electronic beamscanning, accurately identified targets. This missile system combined radar (sensor), a targeting system, and a discriminator, enabling engagement of the target. In subsequent years, the Laboratory made many other contributions to missile system sensors, culminating in APL's appointment as the technical direction agent for the Cooperative Engagement Capability (CEC) program. For CEC, one of our largest programs, the Laboratory developed and integrated sensors and weapons distributed throughout a battle group to work as a single anti-aircraft system.

APL also contributed to the integration of sensors with communications networks for test and evaluation programs. As part of the Trident submarine program, APL installed very wideband sonar recording systems to accurately record the raw acoustic horizon.[1] The Laboratory also developed GPS signal translators and ground-recording equipment, enabling the accurate tracking of the Trident missile.[15]

In 1995, APL launched a program to develop robust time-of-flight (TOF) mass spectrometers capable of detecting airborne chemical and biological agents, drugs, and explosives.[11,12] As part of this program, APL developed enabling technologies for aerosol collection, sample processing, and analysis. Recently, we deployed the next-generation fully automated TOF mass spectrometer with the capability to process threat information in minutes with a very low false alarm rate.

Efforts are also under way at APL to develop terahertz sensors for the detection of landmines and other buried objects.[4] Radiation in the terahertz spectrum (0.1–10.0 THz) has been demonstrated to image subsurface objects with a spatial and depth resolution on the order of millimeters. Furthermore, dielectric materials are transparent in the THz frequency range, which allows imaging through obscurants (fog, dust, haze, smoke, clothing, walls).[16] In recent years, the technology has started to take off, with a large number of promising homeland security applications such as detection of explosives, mines, and biological agents.

Initial development efforts in unattended sensor platform systems and operations demonstrated that data links could be created among remote, unattended ground sensors and space assets using commercial satellite systems like Global Star and Iridium. Future programs will further explore the use of autonomous unmanned aerial vehicles (UAVs) that can cooperate to perform surveillance tasks using adaptive or ad hoc networks based on 802.11 communication protocols. Early testing by APL demonstrated the successful tracking of high-speed missiles in flight using 802.11 links.[17] In another effort, APL also demonstrated that missiles could be equipped with sensors and 802.11 communicators to transmit the data collected by the sensors during high-speed (Mach 2) flight in real time.

From a technology viewpoint, the Laboratory counts several sensors and sensor systems as its major strengths: space-based sensors (magnetometers, UV/visible imagers, charged particle sensors), submarine acoustic arrays, radar systems for guided missile detection, ladar, and chemical/biological sensors. Sensor networks, unattended sensors, and autonomous sensor platforms are also under development (see the article by Watson and Scheidt, this issue). Fully integrated embedded sensor systems where an ensemble of sensors is used to observe large areas (Fig. 1) are becoming increasingly important. Fusion-driven sensor networking is an emerging R&D area at APL that addresses network capacity to support information exchange among a large number of sensors.

The development of sensors and sensor systems at APL is an enterprise-wide activity. Most of the Laboratory's business areas are participating in these and related technologies, including the development of novel communications systems, unattended sensors, GPS technologies, and the next generation of miniature sensors using silicon-on-sapphire electronics and microelectromechanical systems (MEMS). In addition, the information exchange among sensors and airborne collection platforms, satellites, ships, and UAVs is being investigated as part of APL's fusion-driven networking concepts (Fig. 1). The Laboratory's rich history in sensors and sensor systems and its recent contributions lend credence to the fact that, "Sensors have been a key technology area since the Laboratory's beginning. The history of APL could be written based on its sensor development efforts." (A. Kossiakoff, APL, private communication, Jan 2000).

LOOKING TO THE FUTURE

"The fight is now over sensors," said the late VADM Cebrowski in 2003, stressing the importance of sensor system development.[18] Funded by DoD, DARPA (Defense Advanced Research Projects Agency), and industry, research programs are aggressively pursuing the next generation of sensors. These programs are taking sensor development, networking, remote data collection, and miniaturization to the next level.[19–21] Immediate

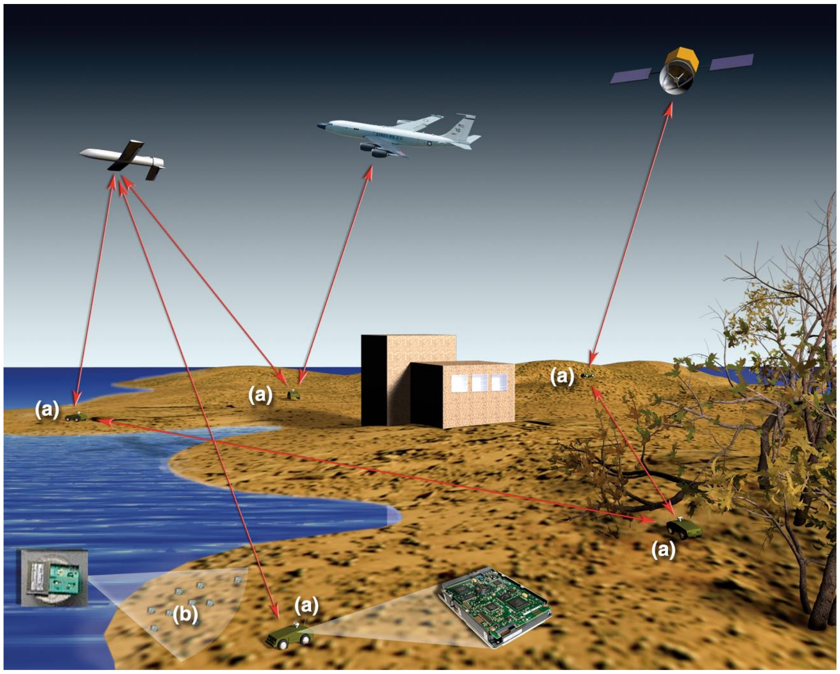


Figure 1. Simplified view of the use of a sensor network for the collection of information. The sensor network communicates with satellites, airplanes, and UAVs. (a) Robotic sensors incorporate MEMS activity, magnetic and acoustics sensors, GPS receivers, and spectral imagers. (b) Air-dropped ultra-miniaturized sensors are part of a larger sensor network. Fusion-driven sensor networking will address the optimum configuration for gateway communications.

payoff in these capabilities will revolutionize the ability of the warfighter to control the future battlefield.

Networking has focused national research because of the vast potential of sensors and information technology to enable users to control and understand the operational environment. Embedded Internet sensing solutions would, for example, allow improved monitoring and transmission of sensor data to and from the battlefield.[22] As stated by a previous Director of Defense Research and Engineering: "Sensors will need to provide a near real-time picture of the battle field and they will need to operate during day, night, and in all weather conditions."[23] This would enable commanders to respond in shorter times to enemy activity.

Besides high-end sensors and sensor systems, visualization of sensor data in real time on geographical grids has taken on increased significance. Visualization laboratories to develop and apply various visualization techniques will emerge and interactively display and visualize sensor data collected by sensor networks in real time. If one considers the entire development chain—from idea, R&D, and prototype development to practical application—it is clear that the sensor developer needs to actively interact across broad research fields to meet the demands of the final user.

Sensor R&D has also advanced electronic miniaturization and the development of new materials (see the articles by Charles and Biermann et al., this issue).

BATTLEFIELD WITH DISTRIBUTED SENSORS

Sensors can be considered the extra "eyes and ears" for soldiers on the battlefield. As part of distributed networks, sensors can offer greatly improved situational awareness. Satellite and airborne platforms (UAVs) can interface with a variety of unattended sensors to collect information from the battlefield environment surrounding the warfighter.

In an urban setting with enemy forces located in and around buildings, a warfighter must rely on accurate intelligence on the location of enemy combatants and weapons. Using a small shoulder-launched UAV, images from this platform are transmitted to the warfighter showing enemy activity. Combined with acoustic information collected by unattended miniature ground sensors, the warfighter is presented with information on enemy location and weapons. Information from the ground sensors and shoulder-launched UAV controller is telemetered to overhead platforms (air-breathing as well as satellite) to a command and control center, which aids the commander in the field.

Especially noteworthy are MEMS, nanosensors, and sensors on a chip (ultrasmall sensor systems called "smart dust").[21,24,25] By combining MEMS, miniaturized digital controllers, and laser-driven communications systems, sensors on a chip can be fabricated. Advances in engineering design have been particularly responsible for creating these microsensors by further reducing their size as well as their power consumption.

It is envisioned that future sensors may include additional functionality and the ability to self-calibrate and occasionally self-repair. Further reductions in the size of the sensing elements and the electric power needed for these sensors have been a significant R&D effort, as noted above. Microscopic surveillance detectors like smart dust and integrated CMOS/MEMS technologies could enable greater use of sensors in large networks. Sensors like these could be deployed in limited-access areas to monitor hostile intentions, dangerous and denied areas, or compliance with international treaties (Fig. 1). In addition, such sensors could be air-dropped in large numbers and interrogated by autonomous vehicles or UAVs, with data relayed to command centers in nearly real time. As mentioned before, the issue of networking the sensors and optimizing those sensors that need to be equipped with communication gateway capabilities will have to be addressed.

The development of sensor networks will play a prominent role in sensor R&D over the next decade. Because of the heightened national security environment, research in sensor networks is in high demand and will continue to intensify in the near future. These developments require sensors that combine a high degree of accuracy, robustness, and reliability operating in "systems of systems" consisting of the information network and the high-bandwidth communications systems. A sensor-based, secure Internet information sensor device would have key opportunities for capitalizing on emerging networks. It is also easy to think of challenging and increasingly refined civilian applications for sensors. Telemetry systems using sensors placed in areas of interest will collect information on traffic and the environment. These data will be transmitting to various users to enable them to see trends and control resources.

The Navy envisions linking sensors and weapons on ships throughout the Fleet as a networked force, with the sensor coverage of individual ships linked to other ships.[23,26] In combination with sensor-equipped UAVs, extensive coverage of sea and land will enable commanders to respond in shorter times to enemy activity. Given the challenges the Navy faces in littoral waters, sensors (radar, video, sonar, acoustic) on unmanned aerial or underwater vehicles will greatly increase mission success by networking these sensors in a comprehensive intelligence toolbox. UAVs will be able to collect information on enemy activity through a multitude of sensors (video, acoustic, deployable sonobuoys, electromagnetic signal analyzers), possibly leading to the deployment of a swarm of miniature UAVs that will have to act as one, combining their individually collected sensor data into a comprehensive intelligence picture using remote networking. Networking of a large number of sensors will be critical to next-generation sensor systems.

The use of autonomous vehicles combined with unattended sensor networks offers a unique opportunity to create a major military strategic advantage for the United States. In addition, a new generation of hyperspectral imagers will be able to detect concealed and camouflaged targets. Placed on UAVs, these sensors will be very valuable in surveying large areas at safe standoff distances.[27–29]

To gain strengthened visibility and national prominence in the development of sensors, APL should continue to focus its sensor and sensor systems development undertakings in several core research areas: mass spectroscopy, web-based sensors, sensor fusion, miniaturization, hyperspectral and microwave/millimeter imagers, and autonomous systems incorporating high data rate signal communications capabilities and ad hoc networks. Efforts at the Laboratory in silicon-on-sapphire and MEMS-based sensors will position APL favorably for the next generation of miniaturized smart dust. Furthermore, APL's contributions in space sensors (particle detectors, radar altimeters, and hyperspectral imagers) will continue to be of major importance to national space programs. In addition, the Laboratory will continue to build on recent major accomplishments in TOF mass spectroscopy to develop a next generation of biochemical sensors. Optimization of dynamic control of resources (sensors and network), combined with sensor fusion, will be increasingly important.

Despite impressive R&D accomplishments in sensors and sensor systems, many opportunities remain for APL to make critical contributions. Developing partnerships through shared information will be particularly valuable for sensor development efforts. Close collaboration with commercial companies and not-for-profit and national laboratories will enhance APL's sensor innovation work. This collaboration can guide new, emerging development efforts and leverage those efforts to hasten the development of new sensor systems benefiting federal programs.

CONCLUSION

Developing sensors and related technologies is important to the Laboratory and to its sponsors, enabling APL to contribute to important national problems.[30] Furthermore, it gives APL a methodology to expand its core capabilities across the enterprise and a means of providing a competitive advantage. Given APL's 60 years of experience in developing sensors and sensor systems, a strong foundation is in place to continue making critical contributions in this field. The Laboratory will also continue to lead sensor development by providing the systems expertise to develop and integrate the next generation of sensors. Future APL contributions will likely come from sensors that are fully integrated in autonomous systems having a high degree of sophistication and operating as sensor networks using the information technology and communications systems of tomorrow. Improving APL's ability to reduce R&D cycles and compress the "concept-to-application" development period will benefit the Laboratory's competitive position as a sensor developer as well. With APL's rich history in developing sensors and sensor systems, many innovations are expected over the next decades.

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THE AUTHOR

Joseph J. Suter received his B.S. (1977) in physics from the Free University of Amsterdam, the Netherlands, and his M.S. (1980) in physics from Michigan State University. Dr. Suter received a second M.S. (1982) in electrical engineering from the University of Maryland and his Ph.D. (1988) in materials science and engineering from The Johns Hopkins University. During the last 22 years, he has led a variety of technical programs involving sensors and communications systems, the atomic and quartz frequency standard, advanced power sources, and spaceflight technologies. He also worked in the APL Office of Technology Transfer as Director of Technology Programs for licensing electronic and communications technologies. Dr. Suter was appointed the Assistant Department Head of the Research and Technology Development Center in 2003 and the Acting Department Head in October 2005. He has (co)-authored more than 58 publications, which have been published in *IEEE Transactions*, *Cryogenics*, the *Journal of Physics D*, the *Journal of Non-Crystalline Solids*, the *Journal of Applied Physics*, and others. His e-mail address is joseph.suter@jhuapl.edu.

Joseph J. Suter