Precision Strike Contributions Selected from the Annals of the *Johns Hopkins APL Technical Digest*

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ABSTRACT

This article summarizes six seminal Johns Hopkins APL Technical Digest *articles that illustrate Johns Hopkins University Applied Physics Laboratory (APL) contributions to precision strike. The articles are described in the context of the historical and operational environments that motivated them. During and after the Vietnam War, the U.S. military needed improved missile guidance and electronic attack. More recently, our military has paid increasing attention to the need for compressed operational timelines, extended engagement ranges, and lower system costs. The summarized articles highlight APL's contributions to meeting these past and current needs. The articles describe historic challenges in and contributions to cruise missile guidance and airborne electronic attack, as well as more recent challenges in and contributions to high-fidelity characterization of enemy radar, hypersonic missiles, data fusion, and dynamic sensor tasking.*

HISTORIC CHALLENGES AND APL CONTRIBUTIONS IN MISSILE GUIDANCE AND ELECTRONIC ATTACK

Although the Precision Strike Mission Area at the Johns Hopkins University Applied Physics Laboratory (APL) and the mission area's organizational predecessors have existed for 20 years, the key challenges of precision strike and APL's contributions to meeting those challenges date back to the Vietnam War era. The enduring precision strike challenge is to attack difficult targets while managing collateral damage and imposing imbalanced costs on the enemy.

During the Vietnam War, some targets were difficult to attack because of their scale (e.g., bridge abutments or dispersed resources as opposed to large, aggregated targets). Attacking small targets meant getting very close, exposing our own forces to risk or destroying much more than the target, with possible consequences including heavy losses and collateral damage. These challenges were addressed by more precisely guided weapons delivered from platforms outside the enemy's reach—for example, air-launched weapons automatically homing on the bright spot illuminated by a laser. As an often-cited example, the United States lost aircraft and pilots while dropping hundreds of bombs on the Thanh Hóa Bridge over the course of 6 years until it was brought down by a small number of laser-guided bombs in April 1972.

During the Vietnam War, U.S. forces met another challenge in facing sophisticated defenses, especially surface-to-air missiles (SAMs). SAMs, of course, had famously proven to be deadly before the Vietnam War when the Russians shot down our U-2 spy plane, piloted by Gary Powers, in 1960. Similar technology was available to our enemy in Vietnam. However, the United States developed the means to counter the SAMs, including jamming the enemy radars that detected and guided the missiles. So-called electronic attack became increasingly capable, precisely exploiting specific enemy radar vulnerabilities.

APL's contributions to meeting these challenges progressed after the Vietnam War along two identifiable lines of innovation. One was improvement in cruise missile guidance and navigation, and the other was airborne electronic attack.

ARTICLE 1: "FIFTY YEARS OF STRIKE WARFARE RESEARCH AT THE APPLIED PHYSICS LABORATORY"

In their historic survey of APL's contributions to strike warfare, Hatch et al.[1] note that accurate missile guidance was foundational; as they put it:

> The Applied Physics Laboratory, with its appreciation for the role of accurate delivery of ordnance gained in the proximity fuze program, stressed the importance of accuracy in minimizing warhead yield requirements and collateral damage to nonmilitary targets.

Our expertise in "accurate delivery" was applied to develop a radar seeker for the Harpoon anti-ship cruise missile in the late 1960s and early 1970s. The success of Harpoon soon led to the Tomahawk cruise missile in both anti-ship and land-attack versions. Tomahawk had much longer ranges and much greater maneuverability than Harpoon, virtues that nevertheless made guiding the missile more difficult. For the land-attack version, APL recommended a missile-borne altimeter that would match land contours with stored elevation maps (with Terrain Contour Matching, or TERCOM). The accuracies achievable under TERCOM were significantly enhanced by the addition of a television camera that took pictures of the area below the missile and matched them to stored geodetically located pictures (with the Digital Scene Matching Area Correlator, or DSMAC). APL improved the algorithms for predicting DSMAC performance (e.g., in planning missions before they are flown) and matching the sensed and stored pictures during the flight. It was compellingly stated that a combination of TERCOM and DSMAC gave Tomahawk the capability to target the pitcher's mound in a hypothetical ballpark hundreds of kilometers away and have an excellent chance of hitting the infield. By the time of the Gulf War, due in large part to APL contributions, cruise missile accuracy had improved so much that selected portions of key buildings could be struck reliably with minimal risk of collateral damage.

ARTICLE 2: "GUIDANCE AND NAVIGATION IN THE GLOBAL ENGAGEMENT DEPARTMENT"

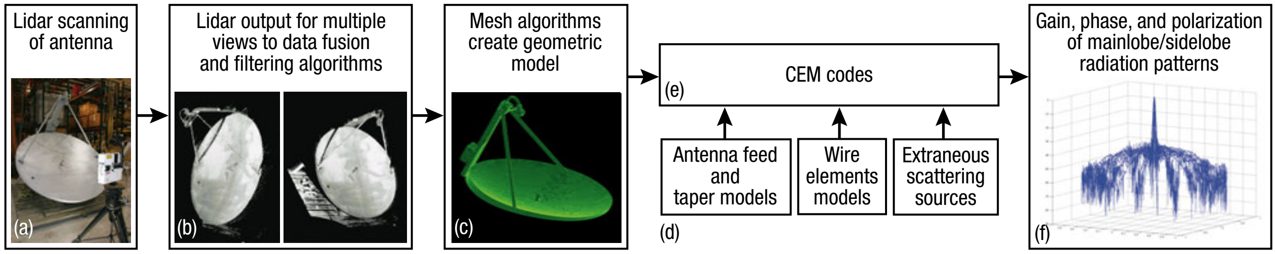
Hatch's story ends in 1992, but APL's contributions to missile guidance did not. Riedel et al.[2] continue the story. As they explain, most modern missiles autonomously track their own location using an inertial navigation system that is both initialized and updated throughout the flight with some external reference, most often the Global Positioning System (GPS). APL has led the implementation of GPS-aided missile navigation. For example, Riedel et al. discuss specific APL contributions in aligning the launch platform's navigation with that of the missile, thus critically initializing the missile's inertial navigation system. During portions of the flight, the enemy may jam the GPS. Riedel et al. also describe APL's development of a technique called Precision Terrain Aided Navigation (PTAN), a refinement of TERCOM, to update the missile's inertial navigation system without GPS. PTAN promised improved accuracy and increased terrain suitability over TERCOM.

Another important element of missile guidance is the ability to approach the target from preferred directions. Riedel et al. describe the contribution APL made to the terminal guidance logic that enabled the missile to fly more accurately into the target from a wider range of angles, thus improving operational employment.

ARTICLE 3: "HIGH-FIDELITY ANTENNA MODELING WITH LIDAR CHARACTERIZATION"

By the time of the Gulf War, APL had also made significant improvements to airborne electronic attack. Those improvements were sorely needed because of the much more sophisticated SAM threat. Many of APL's contributions in this area were not documented in the *Digest* because of their sensitive nature. However, there is one *Digest* article on airborne electronic attack improvements. It was written after the Gulf War on a focused topic but illustrates our ongoing efforts to gain every advantage in airborne electronic attack. The article by Dumm et al.[3] discusses a technique for characterizing the beam pattern of enemy radar much more precisely than alternative techniques. With that information, enemy radars can be attacked electronically from new angles and at greater distances.

Techniques for characterizing radar beam patterns typically rely heavily on interpolation and extrapolation from empirical data limited to scalar gain and single polarization measurements collected over one plane in azimuth and one plane in elevation. The results are inadequate for accurate predictions of the effectiveness of jamming techniques, especially when the jammer is positioned off the victim's main beam. Accurate predictions of sidelobe and backlobe beam patterns are notoriously challenging because of sensitivity to antenna



Summary of the process used to compute high-fidelity antenna patterns. A laser imaging device is used to derive the physical shape of the antenna (a); multiple images of the antenna from distinct angles are captured (b); the images are rotated and translated to a common reference frame and a CAD model of the antenna is constructed (c); models of the antenna feed structure and radiation pattern are developed (d); the feed model and the reflector model are submitted to a computational electromagnetics (CEM) code to compute the far-field radiation patterns of the antenna (e); and the complex-valued far-field patterns for each polarization basis component result (f).

Figure 1. Overview of the high-fidelity antenna pattern characterization approach. (Reprinted from Ref. 3.)

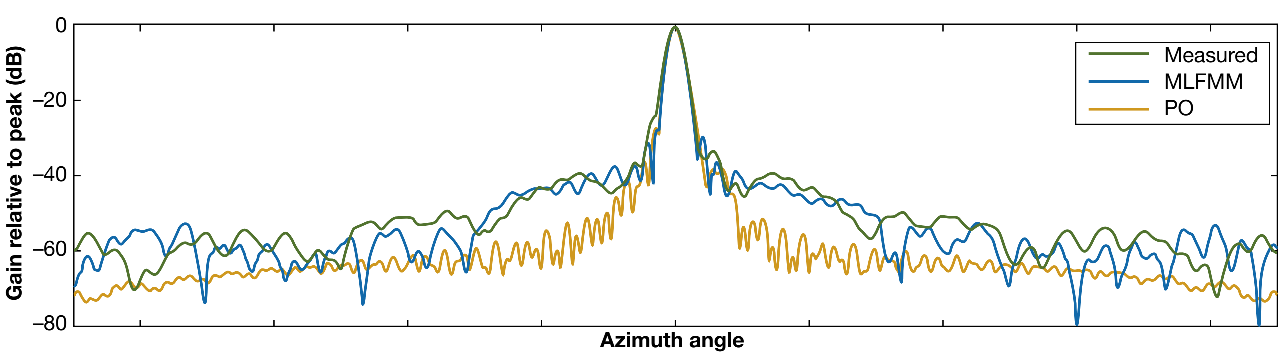
structure and reflecting surface roughness. The technique described by Dumm et al. significantly improves the accuracy through high-resolution imaging and high-fidelity electromagnetic modeling.

Figure 1 shows the process. Images on the left-hand side are for a SPG-62 antenna, the target illuminator for the U.S. Navy's MK 99 fire-control system. The article compares the measured antenna patterns with predictions made from the geometric model based on simple physical optics and on high-fidelity method-of-moments (MoM) computations, specifically the multilevel fast multipole method (MLFMM). A sample comparison of gain around a single azimuthal plane cut is shown in Fig. 2, where the improved accuracy of the higher-fidelity modeling is obvious. The article also discusses the impact of surface roughness and the resulting requirement on how accurate the geometric model must be. The technique has now been used on a number of radars and has become the approach preferred by the electronic attack community for precise antenna beam characterization.

A CHANGING WORLD AND NEW APL CONTRIBUTIONS IN HYPERSONIC MISSILES, DATA FUSION, AND SENSOR TASKING

In a changing world, the advantages produced by our contributions rarely last. The world watched the Gulf War and the war on terrorism carefully, and our enemies learned quickly how to counter our improvements. Missile guidance could be defeated with mobile targets, which can be quickly repositioned. Our accurate missiles are useless if they fly to locations the targets have already vacated. Some of the enemies' high-value targets can move to unpredictable locations within just tens of minutes.

As opposed to operations in the Gulf War and the war on terrorism, an engagement in the western Pacific would force the United States into confrontation at much longer ranges. Figure 3 makes this point by showing the geographic areas and distances over which operations occurred in Iraq and Afghanistan as compared with those in the western Pacific. The largest circles in the map for



Summary of the predicted and measured antenna radiation pattern data for a single azimuthal plane cut. A comparison of the antenna patterns computed using the PO and the MoM-MLFMM methods is shown. The plot is the absolute data normalized to the peak gain.

Figure 2. Comparison of measured and predicted antenna gains. PO, physical optics. (Reprinted from Ref. 3.)

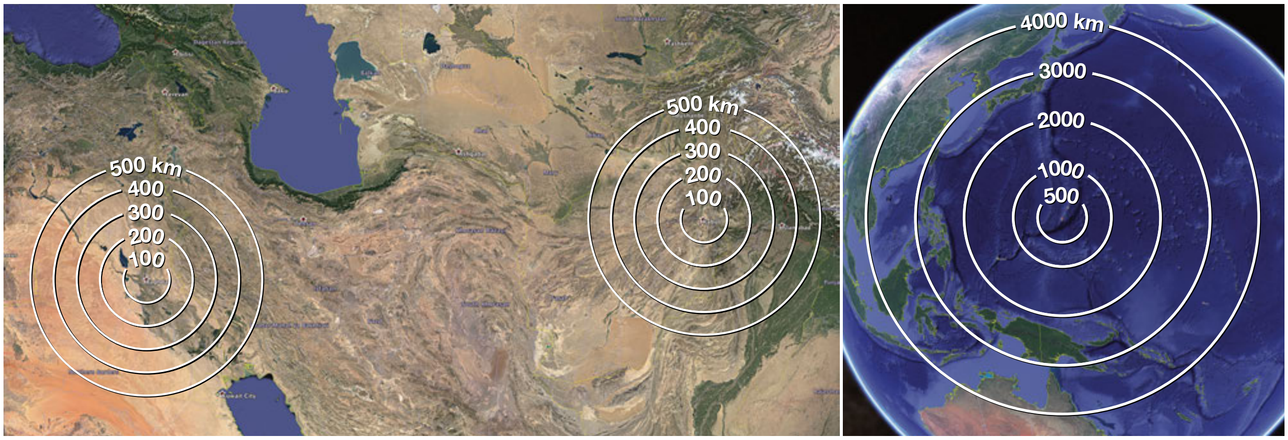


Figure 3. Operational ranges in the Persian Gulf, Afghanistan, and western Pacific. (Left: Google Earth, U.S. Dept. of State Geographer, © 2016 Google, Image Landsat/Copernicus, © 2016 Basarsoft; Right: Google Earth, Data SIO, NOAA, U.S. Navy, NGA, GEBCO, © 2016 Google, U.S. Dept. of State Geographer.)

Iraq and Afghanistan are the same size as the smallest in the map for the western Pacific. Operations in the western Pacific will occur over ranges out to thousands of kilometers and beyond. Furthermore, any confrontation in the western Pacific will occur much closer to the enemy's land than to the continental United States. Our supply lines will be stretched thin. The enemy's weapon stockpile may exceed our deployed inventories of expensive weapons.

A mix of improvements is required to collapse timelines, extend ranges, and impose cost imbalance. Figure 4 illustrates those challenges and options for meeting them. Previously, the United States needed to operate in the upper-left-hand corner of the graph in Fig. 4 (bounded by light green), and we had precision strike options that met those requirements (i.e., air-launched missiles and cruise missiles), albeit at relatively high costs per shot (as indicated in yellow). Now we need precision strike options that reach 100 times farther (e.g., to ~1000 km) and response times that are 10 times faster (e.g., no more than ~1000 s) as shown in the darker green portion of Fig. 4. The previous options do not fall in that quadrant. The cost of new weapons that meet these requirements will be a major consideration.

Fast, long-range, cheap weapons are indicated. As shown in Fig. 5, emerging technologies include more sophisticated airborne electronic attack, ballistic mis-

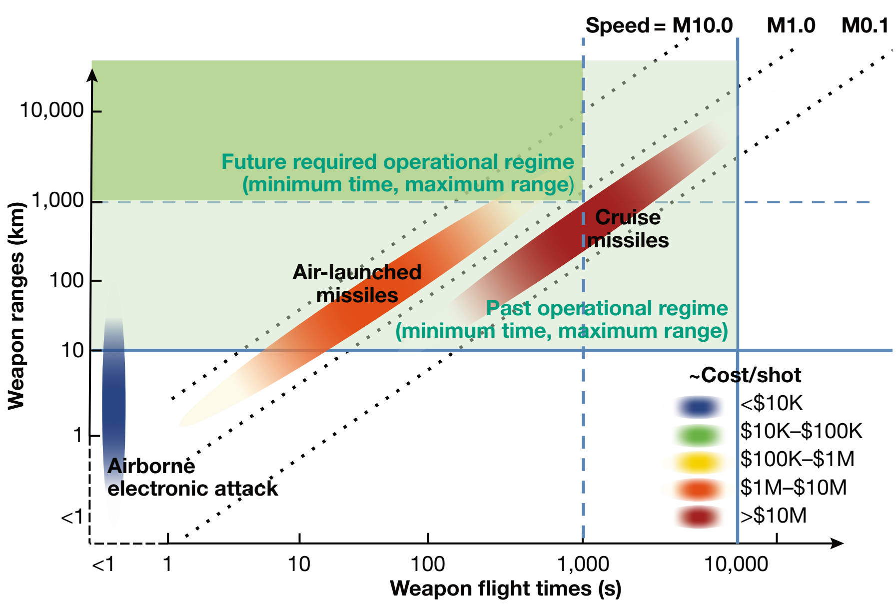


Figure 4. Precision strike weapons circa 1970–2020. Black dotted lines show distance covered over time for constant velocity at indicated speeds. M, Mach number, a measurement of flow velocity past a boundary relative to the speed of sound, which varies with temperature and altitude; at 15°C and at sea level, the speed of sound is ~761 mph, which is assumed here.

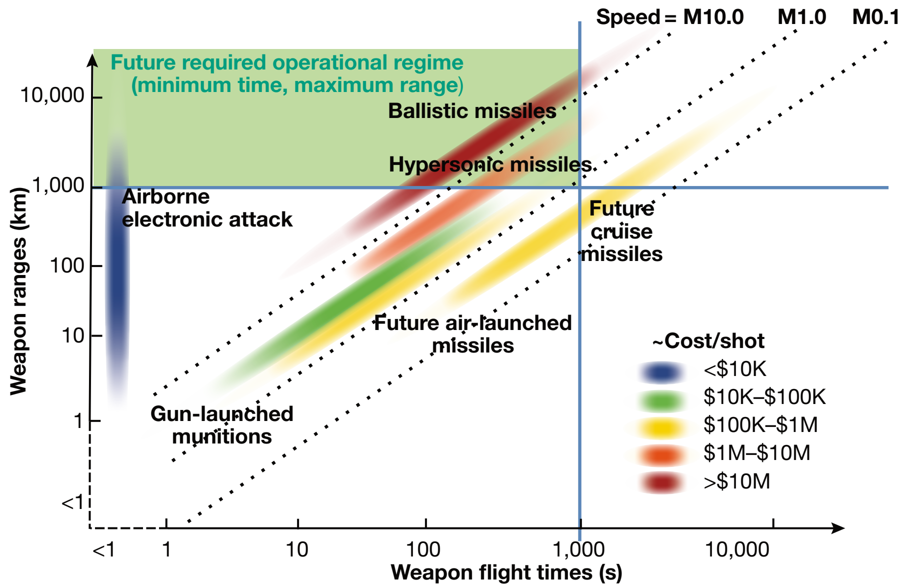


Figure 5. Precision strike weapons circa 2020 and beyond. Black dotted lines show distance covered over time for constant velocity at indicated speeds. M, Mach number, a measurement of flow velocity past a boundary relative to the speed of sound, which varies with temperature and altitude; at 15°C and at sea level, the speed of sound is ~761 mph, which is assumed here.

siles with conventional warheads, hypersonic missiles, electromagnetic railgun, and cheaper air-launched missiles and cruise missiles. APL is making contributions to all those options.

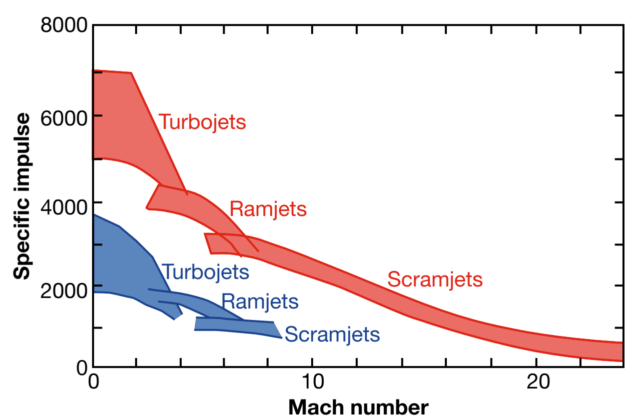
ARTICLE 4: "HYPERSONIC AIRBREATHING PROPULSION"

The article by Van Wie et al.[4] provides an example of APL's contributions to hypersonic missiles. To understand those contributions, it is necessary to understand some of the complexities of hypersonic propulsion.

The article explains that all existing hypersonic vehicles are propelled by thrust from burning hydrogen or hydrocarbons with oxygen in various ways. Airbreathing engines collect all the oxygen they burn from the atmosphere and include different configurations for operating at different speeds as indicated in Fig. 6, which shows the efficiency of turbojets, ramjets, and scramjets as a function of speed. (As explained by Van Wie et al., efficiency is measured as specific impulse, or the ratio of thrust generated to the weight of fuel consumed. Speed is measured in Mach number, or the ratio of vehicle speed to the local speed of sound.) The article notes the following achievements by APL in high-speed engine development.

- The first flight of a ramjet-powered vehicle at supersonic speeds
- Development of the first ship-launched ramjet-powered SAM
- Development and flight-test demonstration of a Mach 4 surface-to-air ramjet-powered missile
- The first demonstration of stable supersonic combustion for propulsion applications
- The first long-duration hydrogen-fueled scramjet combustor tests at speeds greater than Mach 10
- The first successful ground tests at hypersonic speeds of a full-scale, liquid hydrocarbon–fueled scramjet engine integrated into a missile-like configuration

APL is applying the expertise gained through these accomplishments to help the United States develop modern hypersonic missiles to meet the challenges illustrated in Fig. 5. As Fig. 6 indicates, faster means lower specific impulse, hence more fuel and shorter range,



Engine-specific impulse advantages of airbreathing engines (hydrogen fuel, red; hydrocarbon fuels, blue).

Figure 6. Efficiencies of various hypersonic engine types versus speed. (Reprinted from Ref. 4.)

and faster probably also means more expensive. Thus, there are complex trades in making hypersonic missiles faster, able to go farther, and at cheaper cost. APL is contributing to understanding those trades and offering technical advice to the government on design selections.

Faster, longer-range weapons must be accompanied by the rapid means to complete all the steps necessary in a successful engagement (i.e., the kill chain) as illustrated in Fig. 7.

National sensors can provide targeting information at the required ranges but tasking, processing, and dissemination are not fast enough for tactical engagements. For those kinds of improvements, a new approach to the tactical exploitation of national systems was necessary. Such an approach is described in articles 5 and 6.

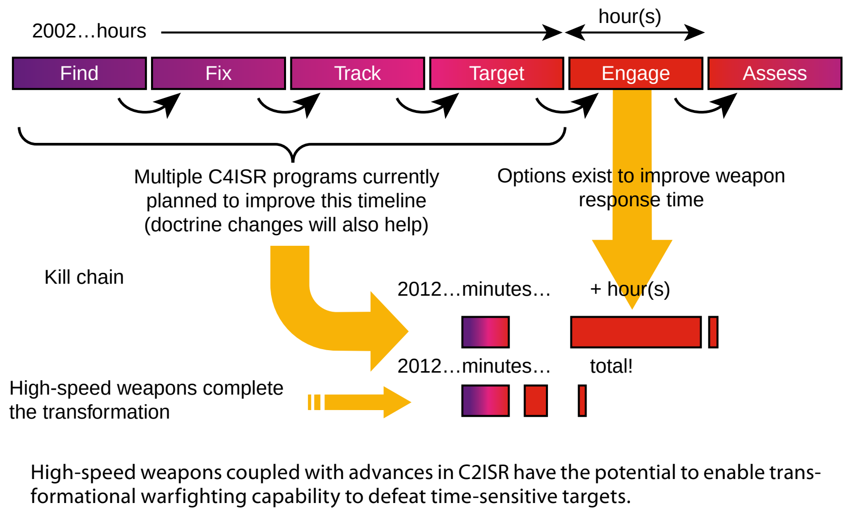


Figure 7. Balancing latency across the kill chain. (Reprinted from Ref. 4.)

ARTICLE 5: "UPSTREAM DATA FUSION: HISTORY, TECHNICAL OVERVIEW, AND APPLICATIONS TO CRITICAL CHALLENGES"

Newman and Mitzel[5] describe a technique called upstream data fusion (UDF) for tapping and combining raw sensor measurements, as illustrated in Fig. 8. The article explains the theoretical benefits of the UDF architecture, not only in timeliness but also in detection, location, classification, robustness to countermeasures, required computational and communications capacity, and asset employment efficiency. The article further describes a series of field UDF demonstrations where those benefits were realized. Some of those demonstrations have focused on time-sensitive targets, thus verifying that the payoff of hypersonic weapons anticipated by

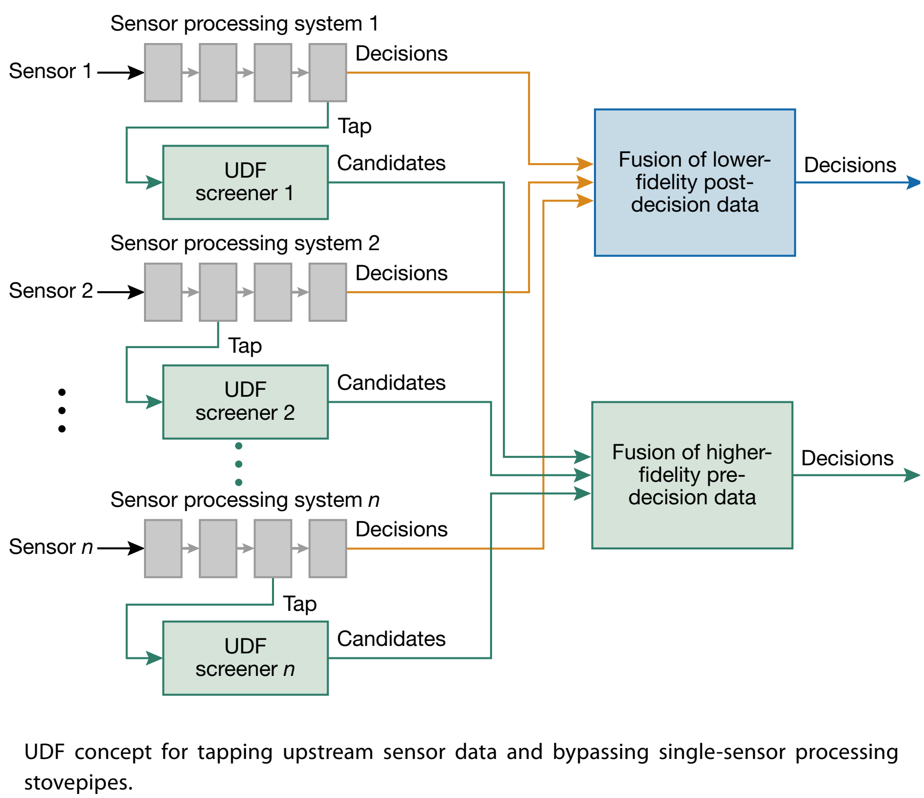


Figure 8. A notional UDF architecture. (Reprinted from Ref. 5.)

Van Wie et al. can be realized at extended range through the use of national sensors.

ARTICLE 6: "CLOSED-LOOP COLLABORATIVE INTELLIGENCE, SURVEILLANCE, AND RECONNAISSANCE RESOURCE MANAGEMENT"

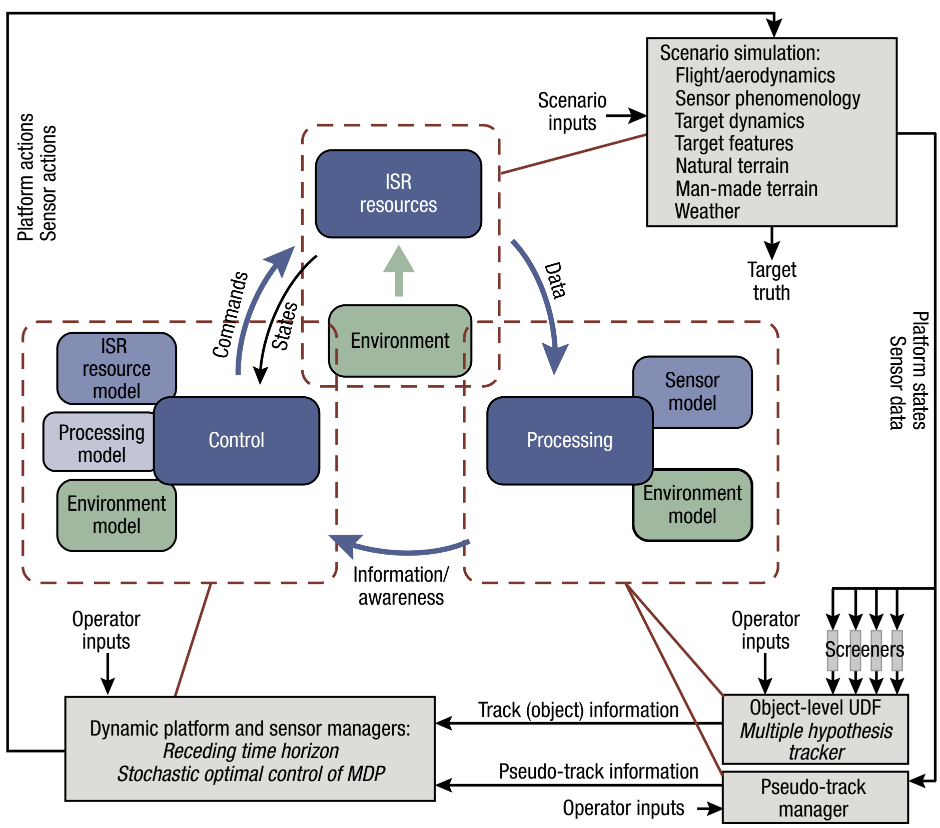
The benefits of UDF will be most fully realized when it is integrated with the capability to task the sensors dynamically, as addressed in a closely related article by Newman and DeSena.[6] Newman and DeSena describe how to use the earliest and sometimes subtle, uncertain, and ambiguous indications from one set of sensor measurements to rapidly task other sensors in a concept they call closed-loop collaborative intelligence, surveillance, and reconnaissance (CLCISR). Figure 9 shows the CLCISR architecture.

The figure shows a functional block diagram depicted within the inner dashed boxes and curved arrows. A prominent feature of the functional block diagram is a main feedback loop that connects ISR resources, processing, and control. ISR resources are sensors of any type that collect data on objects of interest. Data from the sensors are passed to processing. In general, the architecture is designed to handle sensed data in its rawest form, since that is how the greatest UDF benefits will be realized. Processing converts the data to estimates of the presence, location, and classification of sensed objects. Processing also maintains rigorous mathematical assessments of the uncertainties in those estimates. Output from processing is passed to control, which continuously monitors the need for additional data and the opportunities to collect it based on the current and predicted states of the ISR resources and dynamically reallocates the ISR resources accordingly.

Figure 9 also shows a simulation block diagram depicted by the outer gray boxes and straight lines, representing major elements of the Closed-Loop Collaborative Simulation (CLCSim). The simulation has been used to develop future surveillance and targeting architectures against some the nation's most challenging and dangerous time-sensitive targets.

SUMMARY AND CONCLUSIONS

Military threats to our national defense require an arsenal of increasingly more sophisticated offensive weapons. The *Digest* articles discussed here show that APL understands the operational challenges and the technologies



Realization of CLCISR feedback loop.

Figure 9. CLCISR architecture. MDP, Markov decision process. (Adapted from Ref. 7.)

that can meet the challenges. The articles illustrate how APL has applied technologies to make critical improvements in missile guidance, airborne electronic attack, hypersonic missiles, and sensor data fusion and tasking.

The articles also exemplify the holistic approach APL takes to improving precision strike. They illustrate how we seek to balance our contributions across the kill chain. APL constantly strives to integrate our products, although we work for a variety of sponsors in DoD and the intelligence community. Thus, we develop concepts that are very difficult for the government to imagine and build otherwise. As the world grows ever more dangerous, it is this balanced and integrated approach to improving precision strike that positions APL to make even greater contributions in the future.

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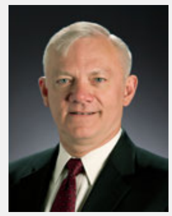

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