An Overview of Information Processing and Management at APL

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Rapid advances in information technology have dramatically affected the manner in which complex systems are developed and used. Yet, despite new capabilities, decision makers are struggling to deal with endlessly increasing amounts and types of data. As a result, APL has been placing additional emphasis on information technology. This article provides an overview of mission-oriented information processing and management at the Laboratory, with a focus on associated science and technology. Consistent with the technology taxonomy developed by APL's Science and Technology Council, four areas are discussed: distributed computing and Web technologies, software engineering and information systems engineering, information operations, and decision support and situational awareness. For each area, historical roots, current Laboratory activities, and critical challenges are described. Recommendations to enhance APL's posture in the field are also offered.

INTRODUCTION

During the past decade, there have been amazing advances in information technology (IT). Global accessibility, high-speed communications, high-performance computing systems, and the World Wide Web have dramatically and permanently changed the nature of business and education. These same capabilities have also affected warfare and space science in ways unimaginable just a few years ago.

But how has APL responded to the rapidly changing IT environment? In the past (and perhaps even today), many would not have characterized APL as an IT organization. Yet a recent survey conducted by the Laboratory's Science and Technology (S&T) Council indicates that about half of the staff are engaged primarily in IT activities. This number is particularly surprising given our recent history. For example, less than a decade ago, one of APL's best-known computer scientists was not hired when he first sought employment at the Laboratory. Although highly regarded for his work as a resident subcontractor, his department simply did not hire computer scientists as APL staff. During the past 5 years, that same department has formed a well-regarded IT group which has sought and succeeded in hiring many computer scientists.

In this article, a high-level overview of information processing and management at APL is provided, with a focus on the S&T associated with the field. In the next section, the field is characterized and four critically important areas identified by the Laboratory's S&T Council are discussed. These areas are then described more fully in subsequent sections. For each, some significant historical events are highlighted, roots at the Laboratory are traced, a number of relevant S&T results are given, and critical challenges facing the Laboratory and its sponsors are presented. In the final section, some details on the state of information processing and management at APL are provided, along with a few thoughts on future S&T directions in the area.

CHARACTERIZING THE FIELD

The technologies associated with information processing and management can be viewed in numerous ways. An academic approach is to identify a set of concentration areas in which research is conducted and courses are offered. For example, in JHU's part-time master of science program in computer science, more than 80 courses are offered in 9 concentration areas: software engineering, systems, theory, information security, information and knowledge management, bioinformatics, visualization and human–computer interaction, data communications and networking, and distributed computing.

Given how new computer science is as a discipline, academic concentration areas are in a continuous state of flux. Only in the last several years, with the advent of the Web, has distributed computing emerged as a distinct area from systems. Similarly, although courses in information security have been offered for many years, only in the past 2 years has security evolved into a standalone area. While new areas are constantly emerging, other areas have evolved or been combined in unanticipated ways. For example, the increasingly important area of information and knowledge management evolved from previous concentration areas that focused on artificial intelligence and database systems. Moreover, the area is heavily influenced by advances in distributed computing, such as eXtensible Markup Language (XML), as a means for building knowledge representations.

Even though an academic taxonomy provides a reasonable basis for delineating research and course offerings, it is not as well suited for characterizing the types of information processing and management activities at APL. Instead, a broader perspective is needed that aggregates areas and reflects the systems context in which information processing and management activities are conducted. There are many different ways to aggregate; however, four areas in particular reflect critical current technologies and serve as a basis for future opportunities: distributed computing and Web technologies, software engineering and information systems engineering, information operations, and decision support and situational awareness.

Figure 1 illustrates the relationships among the four areas. The circular boundary represents the controllable portion of a system. Users within that boundary interact through human–computer interfaces with complex decision support systems. In turn, the decision support systems reside on increasingly distributed computing infrastructures. The infrastructure distributes both computing and data, parallelizes computation as appropriate, and increasingly depends on standard protocols and Web technologies as a means for sharing resources.

The system must also enable people and systems outside the boundary to share and retrieve appropriate information. Thus the boundary also indicates that security measures are required to protect information and systems. Unfortunately, it is impossible to completely protect a sufficiently complex information system; consequently, the protective barrier is porous. For example, unknown software flaws can serve as a basis for attacks, and it is effectively impossible to find all flaws in complex systems. On the other hand, flaws also provide an opportunity to take advantage of unfriendly systems. Information operations reflects both perspectives and provides a means to both protect and exploit information systems.

Finally, the system residing within the circular boundary must be built. The triangular component on the right of Fig. 1 represents the software engineering and information systems engineering effort APL expends to

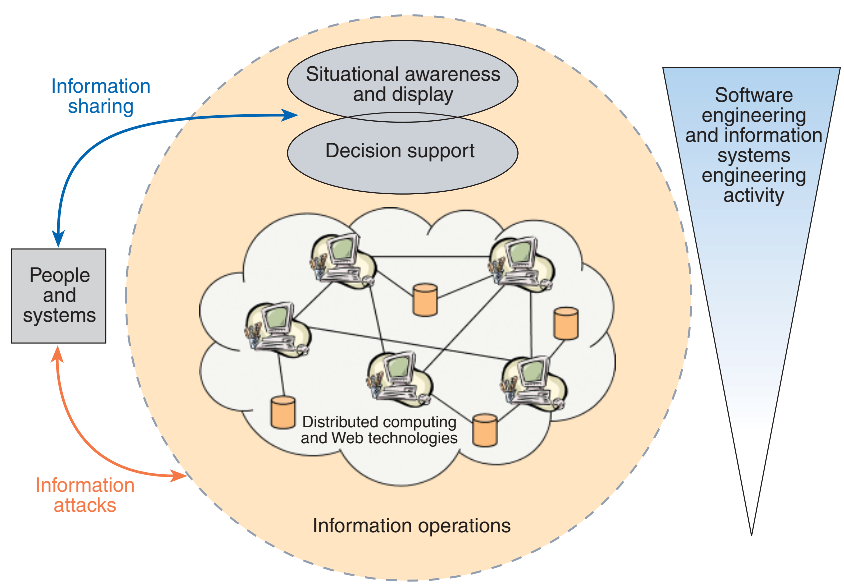

Figure 1. Relationships among APL information processing and management areas.

develop systems. From an S&T perspective, in particular, software engineering and information systems engineering capabilities are most significant with respect to creating complex decision support and situational awareness systems such as the Area Air Defense Commander (AADC) and reliable flight software for spacecraft. Although there are exceptions, the Laboratory has significantly less experience in the S&T associated with developing large-scale Web-based computing or information operations systems.

Distributed Computing and Web Technologies

Distributed computing seeks to provide wider access to information and higher processing performance by enabling computing systems to interact easily. A goal of distributed computing is to shield users and developers from the collection of components that constitute a distributed information system and instead provide a unified view. Underlying technologies in the area include languages such as Java and XML, middleware such as CORBA and Jini, heterogeneous data access, and mobile computing. While still evolving, these technologies are now serving as a basis for many application development activities at the Laboratory.

Sharing of resources is a critical characteristic of unified distributed computing environments. Hardware must be shared to support robust and potentially high-performance computing. Similarly, data must be made accessible to systems at different levels of abstraction. For example, while some systems may only be interested in the exchange of bits that constitute a simple file, other systems may be interested in the exchange of goals to be achieved by intelligent agents acting on behalf of users.

Several events have had a major impact on the nature of this area. Most significant were the creation of the Internet in the 1970s and the subsequent PC revolution of the 1980s. These events set the stage for large-scale information resource sharing. Similarly, the advent of the Web in the 1990s effectively sparked a paradigm shift in the way that systems were built and business was conducted. As Web protocols evolved to provide a standard mechanism for transferring documents, Java emerged as the language of choice for Web application development. Java is the first practical language whose goal is to run on different platforms without recompilation. More recently, XML has provided a standard way to represent information that can dramatically enhance the ability to share different types of data across systems.

APL's experience in distributed computing can be traced to our work in tactical data links in the 1950s and 1960s. This led to efforts in the 1980s that served as a basis for programs such as the Cooperative Engagement Capability (CEC) developed in the 1990s by the Air Defense Systems Department (ADSD).[1] Similarly, starting in the 1970s, the Laboratory began to investigate how networking technology could be used on ships. This led to programs such as HiPer-D in the 1990s. HiPer-D has focused on distributed high-performance computing, including software communications mechanisms, failure management and control, and system execution and monitoring. Extensive work has also been done in the development of distributed spacecraft data processing capabilities to support large-scale space programs such as the TIMED (Thermosphere–Ionosphere–Mesosphere Energetics and Dynamics) mission.

Although still relatively new to this field, APL has several strengths in distributed computing and Web technologies. Most significant is the Laboratory's extensive experience with military networking and distributed sensors. The Laboratory's CEC system, for example, is highly regarded throughout DoD and serves as a model for fusing data from multiple sensors. We are also conducting leading-edge research in the areas of information retrieval and heterogeneous systems integration. In the latter area, the Research and Technology Development Center (RTDC) has developed a prototype system known as the Architecture for Distributed Information Access (ADINA) which can accept a high-level query, decompose and distribute the request across several databases, automatically generate relevant subqueries, and fuse the results into a cohesive response.[2] Finally, the Laboratory has been exploring the use of intelligent agents as a mechanism for autonomous control to support distributed ship systems automation. In particular, the National Security Technology Department's (NSTD) Open Autonomy Kernel System supports a framework for hierarchical planning using a model-based reasoning approach.

During the past few years, the Laboratory has developed some renown in distributed computing. In the 1990s and 2000s, for example, Marty Hall published two editions of a book on Web programming[3] and a book on servlets and JavaServer pages, with a second edition in press.[4] These were among the best-selling computer science books in the world. They have been translated into numerous languages and used by many universities and professional developers around the globe. Hall also trained a large fraction of APL's staff who have competency in Web technologies. From a research standpoint, the Hopkins Automated Information Retriever for Combing Unstructured Text (HAIRCUT), developed by RTDC scientists, has been recognized as one of the top-performing cross-language information retrieval systems in the world (Fig. 2).[5,6] Through the use of novel analysis and search techniques, the HAIRCUT system is able to accept inputs in one language, such as English, and return relevant documents in another language, such as Arabic.

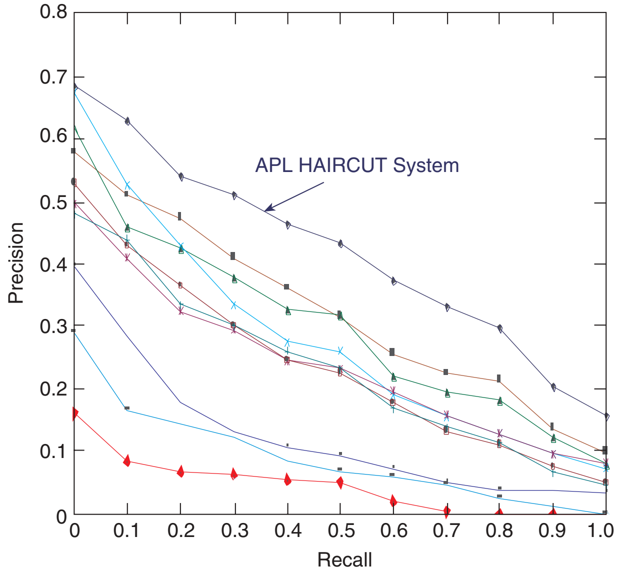

Figure 2. Results from a recent international Cross-Language Evaluation Forum (CLEF-2000) task. The challenge was to find relevant English documents from a selected European language, without human intervention. Greater area under a curve indicates higher system retrieval performance.

While there have been great advances during the past few years in distributed computing and Web technologies, several key challenges remain for APL and our sponsors. First, it is still difficult to integrate heterogeneous data sources. For example, a commander or analyst wishing to pose an *ad hoc* query about the status of enemy forces using information that resides in multiple databases requires extensive knowledge of corresponding underlying systems and the ability to merge potentially conflicting data and inconsistent data types on multiple computing platforms. XML provides a starting point for resolving such issues, but additional work is needed to develop effective ways to share diverse sources of information. Second, APL sponsors employ a tremendous amount of legacy software (e.g., for scientific data access and intelligence applications). If these systems are to remain viable in a modern setting, they will likely have to be made accessible through Web technologies. Finally, users are demanding that their systems be more robust and scalable. Specialized parallel processing approaches have been developed for selected applications, but they have been expensive and difficult to generalize. Instead, better techniques are needed to take advantage of distributed computing resources, for both performance and reliability; however, these techniques must not result in significantly greater complexity for software developers.

Software Engineering and Information Systems Engineering

While distributed computing and Web technologies provide an infrastructure for system deployment, engineering a large-scale system remains an immensely complex task. Software engineering and information systems engineering seek to address this complexity through disciplined approaches to the analysis, design, and development of systems. Specific technologies that are fundamental to this area include layered and modular architectures, validation and verification, quality assurance, and configuration management.

The term "software engineering" was coined at a 1968 NATO conference. A few years later, Brooks' influential book, *The Mythical Man-Month*,[7] was published. It described the complexity of large-scale software development as well as the fallacy that employing more developers on a project would necessarily accelerate progress. In the 1980s, the highly regarded Software Engineering Institute at Carnegie Mellon University was created, and process models such as the Capability Maturity Model (CMM) were developed. In addition, approaches to software development based on structured and object-oriented techniques became mainstream. During the past few years, there has been a push in industry to use lightweight software processes, such as eXtreme Programming (XP), which stress rapid development, frequent builds, and extensive interaction with users.

APL has a long history in software engineering. Starting with the mainframe era in the 1960s (Fig. 3), Laboratory staff were early adopters of (at-the-time) high-level languages such as Fortran and PL/1, and later developed niche expertise with languages such as Lisp

Figure 3. APL's IBM 360 mainframe and memory board from the 1960s.

and Iverson's Language (also known as APL) for work in artificial intelligence and mathematical processing. In the 1970s, the Laboratory developed the capability to upload software to satellites to support the Space Department's Transit Improvement Program (Fig. 4).[8] Several years later, Bruce Blum, a well-known software engineer at APL, began working with the JHU School of Medicine and developed The Environment for Developing Information Utility Machines (TEDIUM), which was a platform for engineering large-scale information systems primarily in the medical informatics community. Blum went on to publish extensively in the field, including three books on software engineering.[9–11] During the past year, more APL staff have recognized the importance of formal software engineering methods, and a team was set up by the S&T Council to explore actions APL should take to improve software processes. The team developed a set of recommendations accepted by the Laboratory's Executive Council that will require more formal approaches to software development and could enable organizational elements of APL to pursue higher CMM levels.

The Laboratory's greatest strength in software engineering and information systems engineering is its stable staff of developers. Over the course of many years, these staff members have developed a great appreciation of sponsors' needs as well as a deep understanding of sponsors' legacy systems. Our systems perspective and specialized facilities also provide a solid basis for the development of large-scale systems such as the Trident D5 software developed by the Strategic Systems Department and the NEAR Mission Operations Center developed by the Space Department.

Figure 4. Artist's conception of a satellite for the Transit Improvement Program. Software was uploaded to Transit satellites to control operations.

Much of the software being developed at the Laboratory today is for decision support, and some is near the forefront of software engineering and information systems engineering technology. For example, the service-based combat systems architecture being developed by NSTD is built on leading middleware technologies such as Jini. The architecture is designed to create a network-centric combat system that is self-configuring, self-updating, and self-healing to enhance interoperability in support of battlespace awareness. Similarly, projects are under way in the Space Department to develop comprehensive processes for software testing and to create reusable planning tools. These projects are seeking to improve the robustness and reliability of developed software, and to ultimately reduce mission operations costs.

Looking to the future, one of the greatest challenges that we face in software engineering and information systems engineering is endemic to all organizations that develop large-scale software systems: dealing with tremendous complexity. Systems that comprise many thousands or even millions of lines of code must be carefully planned and constructed. CMM processes and performance-enhancing tools and techniques are useful, but they require additional commitment throughout the Laboratory. Integration and interoperability pose another significant challenge. In particular, there is an enormous investment in existing software systems, and reengineering these systems to provide capabilities based on the latest technologies typically is not viable. Instead, improved approaches are needed for incorporating legacy and new systems into cohesive applications. At the same time, there is an increasing reliance on commercial off-the-shelf (COTS) technologies and a desire for faster development cycles. Emerging technologies such as component-based architectures, software frameworks, and patterns that facilitate development can support solutions to these challenges.

Information Operations

During the past few years, it has become routine to hear about viruses and worms unleashed over the Internet that cause incredible amounts of damage. For example, the Love Bug, which had on the order of 50 variants, was estimated to have affected 40 million computers and cost $8.7 billion in repairs and lost productivity.[12] Furthermore, resources are readily available on the Web to assist hackers who want to find and exploit flaws in software systems for malicious purposes. Information operations seeks to protect friendly information systems while exploiting those belonging to adversaries. The defensive component is referred to as *information assurance*, and the offensive component is referred to as *information warfare*. Relevant technologies include intrusion detection, multilevel security, cryptography, and information operations weaponry.

Although considered a new discipline, information operations has roots in ancient Greece, where the first encrypted messages were sent.[13] More recently, the cracking of the Enigma cipher in the 1940s provided intelligence that was instrumental to the Allied victory in World War II. The modern age of information operations can be traced to the 1970s with the emergence of the Internet and distributed computing. To protect data over networks, sophisticated encryption algorithms were developed; however, distributing keys became increasingly difficult. In particular, secure distribution of keys required a physical transfer, which limited the number of people that could send or receive protected information over a large network.

The creation of public key cryptography, based on asymmetric keys, provided a reasonable solution to the distribution problem, although the security is ultimately based on unproven hypotheses in number theory. The use of the technology is also straightforward. Suppose, for example, that a person, traditionally known as Bob, wants to send Alice a message. Bob looks up Alice's public key in a directory widely accessible over the network. Bob encrypts his message using that key and sends the message to Alice. In turn, Alice uses her private key, which she has not shared, to decrypt the message. An eavesdropper, even though having access to Alice's public key, is not able to decrypt Bob's message.

While cryptography provided a way to protect data, systems still became increasingly vulnerable to attack. In the 1980s, for example, viruses and worms were developed that inspired the more sophisticated, but indiscriminating, threats frequently heard about today. In addition, specialized denial-of-service attacks were created that flooded system queues to prevent valid messages from being received. The increasing reliance on COTS technology has also posed a problem, enabling hackers to focus efforts, even if unintentionally, on standardized systems. Moreover, flaws introduced in new COTS releases often supersede protection schemes that evolve in response to discovered attacks.

APL's roots in information operations can be traced to the 1980s with the Navy Vulnerability Assessment Program, which sought to identify security issues with radio-frequency data links. However, the Laboratory did not became seriously engaged until the 1990s, when researchers developed the first operational quantum cryptography systems that worked over fiber and in free space (Fig. 5).[14] Quantum cryptography overcomes any risk associated with being able to factor numbers and thus discover the keys used in traditional public key cryptographic systems. In particular, the technology relies on the uncertainty principle to create what amounts to secure one-time pads that cannot be cracked. Furthermore, eavesdropping can be detected, which ensures that the security of distributed keys can be guaranteed. Although this may not appear to be a serious issue today because of the assumed exponential complexity associated with factoring numbers, quantum computers, if they are built, will be able to factor keys very quickly, and will thus negate the security of present-day systems.

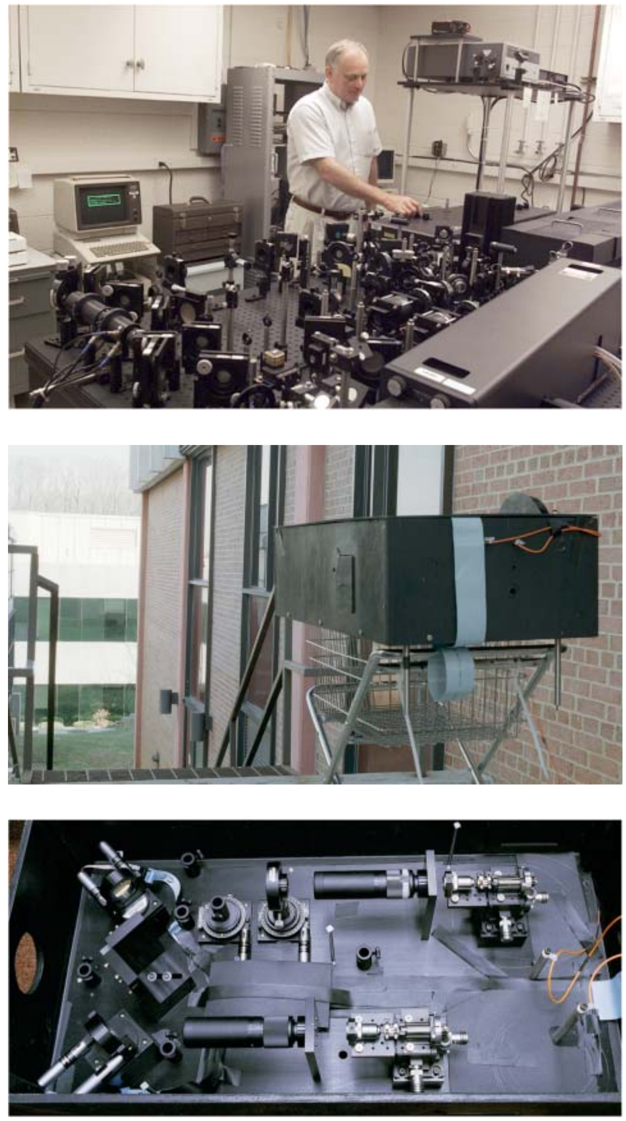

Figure 5. From top, APL's Quantum Information Laboratory, and examples of the Laboratory's free-space and fiber quantum cryptography systems.

The Laboratory has also made significant inroads into broader-based information operations activities. Many of these activities can be traced to an extensive strategic planning effort undertaken by the Power Projection Systems Department (PPSD) in the late 1990s, which identified information operations as a critical area. Since then, new programs have been established that relate to intrusion detection and information assurance, and key staff members have been placed at the National Security Agency. A culmination of these events was the naming of APL as NSA's enterprise systems engineer and the establishment of information operations as one of the Laboratory's business areas in 2001.

In addition to world-renowned expertise in quantum cryptography and quantum computing, APL has several other strengths in information operations. In particular, staff members are able to employ a disciplined and generalizable systems engineering approach for characterizing what constitutes normal and anomalous behavior in information systems. The Laboratory also has a thorough understanding of the challenges associated with classified information processing, which can serve as a basis for developing tools and techniques to secure a wide variety of sensitive information systems. Moreover, APL has significant experience in implementing security solutions in warfighting environments, especially aboard ships.

Current S&T efforts in information operations are varied. From a long-term standpoint, RTDC scientists are developing optical approaches that could lead to the realization of a scalable quantum computer.[15,16] Although the impacts of quantum computing range well beyond information operations, there are immediate intelligence needs to which the technology could be applied. From a nearer-term perspective, PPSD has developed an intrusion detection system that uses neural networks to protect the Army's Lower Tactical Internet against novel attacks.[17] In addition, a combination of intrusion detection techniques is being used to secure CEC computer networks. Staff members are also working with the Defense Advanced Research Projects Agency (DARPA) to quantify the effects of denial-of-service attacks and to develop mitigation strategies. Distributed denial-of-service attacks, in which attacks are coordinated across a set of computers rather than originating from a single source, are also being considered. Finally, ADSD has developed techniques for protecting critical information assets and real-time systems based on a combination of layered software and hardware techniques.

A critical challenge in information operations is how to balance system functionality and security. At one extreme, a computer can be locked in a room and not connected to any network. While the system would be relatively secure, it would not be particularly useful in today's highly connected environment. At the other extreme, complete access to and from any network resource makes the computer quite vulnerable to attack. The goal is to find unobtrusive ways to protect systems that maximize connectivity but do not compromise usability. Another significant challenge is the development of evolutionary security capabilities, especially in dynamic environments where both computing and attack technologies change rapidly. Although biologically inspired models offer some promise, no comprehensive solution has yet been developed.

Decision Support and Situational Awareness

APL's flagship area in information processing and management is decision support and situational awareness. Decision support systems are designed to facilitate planning and execution, the development of alternative courses of action, resource allocation, and follow-on execution. They thus play a particularly important role in command and control. Situational awareness focuses on fusing, selecting, and presenting information. A goal is to create a picture of the operational environment that presents the right information in the right way to enhance decision making. Important technologies in this area include planning, knowledge-based systems, reasoning under uncertainty, visualization, and human–computer interaction.

As with information operations, it is possible to trace the roots of decision support and situational awareness into antiquity. For example, the ancient Greeks used signal flags to communicate among ships. More recently, wireless communications were employed in the 1920s as a means for rapidly disseminating information across wide areas. In the 1970s, artificial intelligence and expert systems techniques were developed to represent and use a decision maker's knowledge to generate prioritized courses of action. Several years later, data fusion technologies were developed that enabled the integration of information from disparate sources, and command and control architectures were developed that sought to take advantage of the new information available. Finally, in the 1980s and 1990s, automated planning tools and sophisticated human–computer interaction capabilities were created to enable decision makers to better understand the operational environment and act accordingly.

APL has had a distinguished history in decision support and situational awareness. For example, during the 1950s and 1960s, the Laboratory was critically engaged in the development of weapon control systems and the Navy Tactical Data System (NTDS), and performed the first experiments on commanders' use of automated decision support systems. Researchers also began exploring mobile automata, developing two robots affectionately known as Ferdinand and the Hopkins Beast (Fig. 6). Ferdinand and the Beast demonstrated primitive situational awareness as they roamed the halls of APL, avoiding obstacles, stairs, and open doorways, and accurately locating and attaching to electrical outlets to recharge their batteries. Significantly, these devices presaged ideas becoming popular today. For example, a feature of the Army's Future Combat Systems program is the planned use of small robotic devices that will roam the battlefield to collect information and support combat operations.

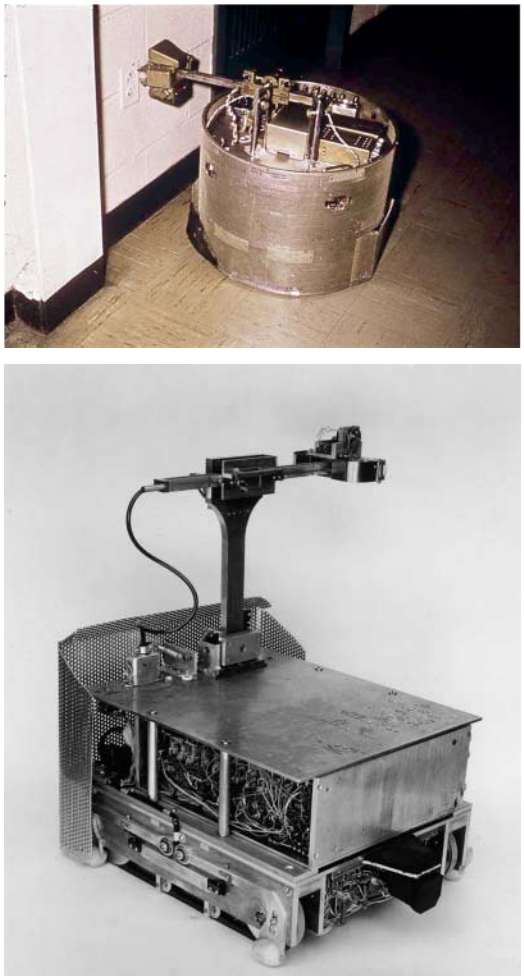

Figure 6. Early automata at APL: Ferdinand (top) and the Hopkins Beast (bottom).

During the 1970s and 1980s, APL played a key role in the development of Aegis display and automation concepts, and was also engaged in developing initial Tomahawk mission planning and weapon control systems. In the 1980s, techniques for establishing a common geographic reference frame (i.e., advanced gridlock) were developed, and expert systems were created to support signature management for submarines and network control for satellite communications.

The 1990s were highlighted by the development of the Force Threat Evaluation and Weapon Assignment system, AADC, and CEC (Fig. 7). At a lower level, the Common Display Kernel was created to support the construction of complex tactical graphics systems. Similarly, prototypes were developed to support the automation of ship systems using intelligent user interfaces to enable ship operation with fewer people. In addition, Tomahawk decision support was extended to enable multiple hypothesis tracking. New tools such as QUICK (which stands for "QUICK is a Universal Interface with Conceptual Knowledge") and the Integrated Vulnerability Management System (Fig. 8) were developed to support automated query formulation over complex databases and the comprehensive management of threats that a ship or, more broadly, a force might face. Significantly, many of these systems continue to evolve and have been successfully employed in real-world settings.

APL has maintained considerable strengths in decision support and situational awareness. For example, the Laboratory's role as the Technical Direction Agent for Tomahawk has enabled us to influence and guide the development of decision support technologies for one of the world's most effective modern-day weapon systems (Fig. 9). APL has also developed relevant systems engineering capabilities for its work on Aegis and the Ship Self-Defense System. Moreover, the Laboratory has become renowned in the DoD community for building Navy sensor fusion systems such as CEC and situational awareness and display systems such as AADC. Finally, APL has developed a long-term appreciation for and deep understanding of Navy and NASA

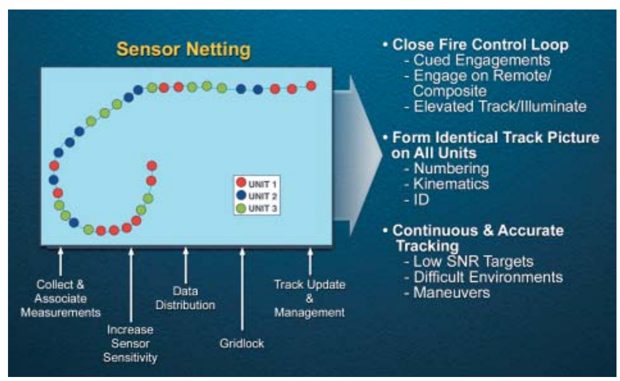

Figure 7. The CEC concept (top) and AADC in operation (bottom).

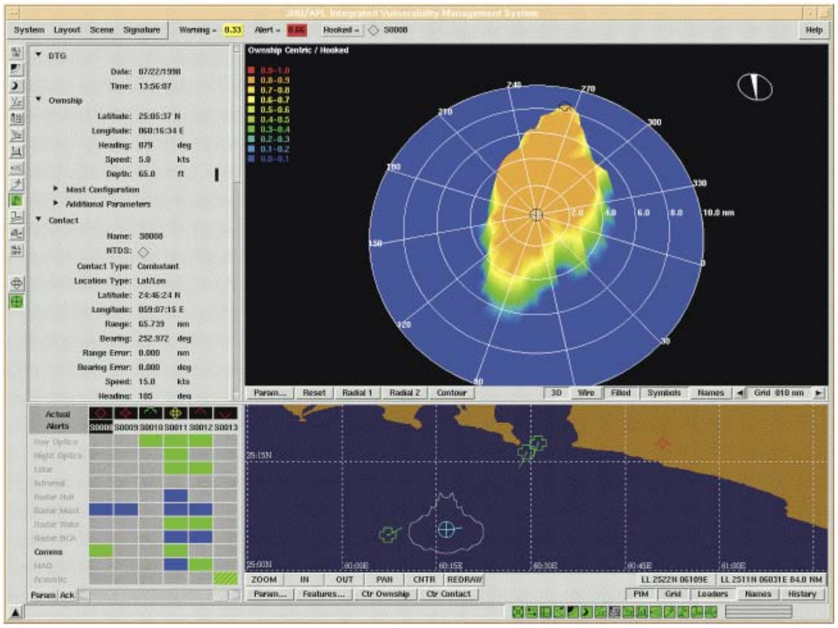

Figure 8. Sample display from the Integrated Vulnerability Management System.

Figure 9. Tomahawk in flight (top) and the Tomahawk Strike Execution Laboratory (bottom).

operational needs, which has enabled us to create highly relevant and sought-after systems.

Building on our strengths, the Laboratory is engaged in numerous decision support and situational awareness S&T activities. Engineers in PPSD, for example, have been investigating innovative planning techniques based on evolutionary programming for weapon system control to support rapid strike planning. Similarly, the Space Department has been developing techniques for intelligent control of spacecraft, with an ultimate goal being to support what former NASA Administrator Dan Goldin referred to as a "thinking spacecraft."[18] With AADC, ADSD engineers have developed parallel processing techniques to optimize air defense asset allocation, and have created complex three-dimensional visualization capabilities and embedded decision aids to help users assess battlespace activity. For CEC, engineers have created real-time planning aids for air defense as well as multisource data fusion capabilities to support tracking, track identification, cooperative decision making, and engagement coordination. In addition, the Laboratory has integrated data fusion systems with real-time planning tools to monitor threat coverage.

Probabilistic approaches for decision support have also been gaining in importance. For example, ADSD engineers have developed reasoning engines using Dempster-Shafer and Bayesian theory to investigate composite combat identification based on combining surveillance and identification data within a network of platforms. Various filtering approaches have also been developed to support the augmentation of global track pictures with optimized tracking models to reduce measurement noise. RTDC researchers have been investigating the fundamental underpinnings of Bayesian Belief Networks, and have developed approximate approaches based on statistical physics that, for a large class of problems, overcome the inherent exponential complexity associated with traditional Bayesian approaches.[19] These techniques are now being explored for use in target discrimination as well as in the increasingly important field of bioinformatics.

The Laboratory is also developing capabilities to enhance satellite network control. In particular, PPSD engineers have developed a system that has worldwide viewing capabilities to provide enhanced decision support and to speed problem detection. Furthermore, future tools are being designed to support problem diagnosis, troubleshooting, and resolution. Finally, Joint Warfare Analysis Department engineers have conducted a preliminary investigation into how collaborative robotics could be used to support situational awareness in high-risk environments.

Despite APL's strong position in this area, there remain significant challenges associated with decision support and situational awareness. First, better capabilities are needed to support very fast planning and replanning that involve many systems and few people. This will become particularly important as hypersonic missile technology evolves and the need to quickly engage mobile targets increases. A second challenge is the requirement to use and fuse an increasing number of information sources, which are becoming more diverse (e.g., semi-structured data and real-time video). Finally, as systems are merged into "systems of systems" and connectivity among these systems increases, the need for seamless interaction will become much more important.

CONCLUSIONS

Information processing and management is a field of significant and increasing importance to the Laboratory. Although APL has made contributions in each of the four areas discussed in this article, there remain opportunities and steps that can be taken to enhance the Laboratory's capabilities in the field.

A near-term recommendation is to incorporate distributed computing and Web technologies more extensively in APL programs, especially those that may require the integration of multiple information systems. Similarly, the Laboratory should embrace software engineering as a discipline while considering how to establish flexible processes to support the development needs of individual business areas. The Laboratory should also recognize the relative immaturity of information operations and seek to become an information assurance center of excellence for selected sponsors. Finally, for decision support and situational awareness, APL should consider how to develop greater joint service expertise, and anticipate and respond to the impact of emerging distributed computing technologies on future systems.

From a broader perspective, we should continue seeking deeper S&T expertise in the information sciences and should broaden our thinking about the capabilities needed for emerging business opportunities. For example, wireless communications and handheld computing are likely to have a profound impact on command and control systems during the next several years, and the Laboratory needs to be prepared to take advantage of the new capabilities that these technologies will provide.

Finally, APL should seek to keep its staff current on information sciences and technology areas that will be of lasting importance such as data mining and fusion, cognitive science, information security, knowledge management, and information system architectures. Moreover, the Laboratory should participate more in professional and government IT activities, and engage academia and industry more extensively to ensure that we retain access to the forefront of IT and can thus better respond to emerging critical challenges.

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ACKNOWLEDGMENTS: The author gratefully acknowledges the presenters in the information processing and management session of the second Senior Leadership Team Technology Review. Special thanks for assistance with the plenary presentation upon which this article is based are extended to Harry Charles, Rose Daley, John Gersh, Donna Gregg, Bob Grossman, Marty Hall, Art Krummenoehl, Mark LoPresto, Dan Phillips, Dave Restione, Paul Schuster, Chuck Sinex, Pam Smith, Dan Sunday, Lora Suther, Dave Thayer, Dave Watson, Miller Whisnant, and Lew Zitzman.

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