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Review of defense display research programs *

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ABSTRACT

Display research has comprised a substantial portion of the defense investment in new technology for national security for the past 13 years. These investments have been made by the separate service departments and, especially, via several Defense Advanced Research Projects Agency (DARPA) programs, known collectively as the High Definition Systems (HDS) Program (which ended in 2001) and via the Office of the Secretary of Defense (OSD) Defense Production Act (DPA) Title III Program (efforts ended in 2000). Using input from the Army, Navy, and Air Force to focus research and identify insertion opportunities, DARPA and the Title III Program Office have made investments to develop the national technology base and manufacturing infrastructure necessary to meet the twin challenge of providing affordable displays in current systems and enabling the DoD strategy of winning future conflicts by getting more information to all participants during the battle. These completed DARPA and DPA research and infrastructure programs are reviewed. Service investments have been and are being made to transition display technology; examples are described. Display science and technology (S&T) visions are documented for each service to assist the identification of areas meriting consideration for future defense research.

Keywords: displays, flat panel displays, electron devices, electronics, electro-optics, visual display systems and components, direct-view, projection-view, see-through, miniature displays, high definition systems, human system interfaces, crew system integration, situational awareness, information dominance, cockpits, crew stations, anchor desks, simulators, synthetic vision systems, night vision systems, mobile communications, team decision suites, wall display systems (knowledge/data/images), exterior display systems (vehicle surfaces, building facades), custom-design, consumer-design, ruggedization, affordability

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1. INTRODUCTION

1.1 The Display Science and Technology Challenge

Displays technologies, in one form or another--whether well advanced amorphous silicon active matrix liquid crystal displays (a-Si AMLCD) and digital micromirror device (DMD) projection displays, or some future contender, such as organic light emitting diode displays (OLED)—will be installed via military avionics, vetronics, or shipboard electronics throughout DoD. This situation is not merely because flat panel displays (FPDs *) have the readily apparent advantages of less weight, volume, and power consumption relative to the older technology cathode ray tube (CRT) and electro-mechanical (EM) displays, but also by virtue of a many-fold increase in reliability that produces a substantial life-cycle cost (LCC) reduction with return on investments (ROI) typically 12:1. Advanced digital display technologies improve availability and cost less to operate. For this reason FPDs will eventually find their way into even benign-environment DoD-unique applications such as weapon system trainers and command and control stations. It is important to facilitate the decision process, by DoD and industry, which leads to putting the requisite size, number, and kind of displays into military platforms in a timely manner.

All DoD science and technology (S&T) organizations recognize a responsibility to the warfighter, the maintainer, and the taxpayer. Bringing military FPDs into the DoD inventory on a timely basis will serve the warfighter by providing a more mission-capable piece of equipment, which reduces spaceman/airman/soldier/marine/sailer/seal workload while improving situational awareness (SA) and combat kills. The maintenance establishment is served (1) by reducing workload and need for spares due to a FPD mean time between failure (MTBF) rate 30-100 times less than the out-going technologies and (2) by addressing the vanishing vendor syndrome (VVS) for fielded military EM and CRT displays. The taxpayer is served first (1) by decreasing expenditures and (2) by ultimately reducing the projected number of persons and platforms necessary to achieve availability and sortie rates sufficient to provide the defense capabilities required by national military objectives.

The overall DoD flat panel challenge is to develop capable crew display systems for all classes of air, space, land and water vehicles, with spin-off to and spin-on from other federal, university, and civil dual uses. The primary goal is to develop affordable, capable crew station display technologies. A second goal is to conceive human system interfaces that use all the warfighters' sensory modalities–vision, touch, hearing, et cetera–in order to "embed" them in the information flow. The third goal is to establish cross-service display hardware and symbology standardization for economy of scale production runs, reduced logistics "tail", and safety. Objectives include display technologies not subject to the vanishing vendor syndrome (VVS) and resolution increases well beyond 1280 x 1024 color pixel video Vehicle-Mounted Displays (VMD), Head-Mounted Displays (HMD), Synthetic Vision Systems (SVS), and Wall Display Systems (WDS). Tri-service logistics centers, depots, and system program offices are requesting S&T help at an ever-increasing rate for retrofits at the 1.3 Mpixel and less regime. A key role of the service laboratories is to make DoD a "smart buyer" of new display technologies in retrofitting current as well as new systems. Many display retrofits are made mandatory by the VVS. Long-range goals include the capability to put pixels on the head, vehicle/console, or wall according to the following timeframe (full color, full motion video in all cases): 10 megapixels per person by 2005; 35-210 megapixels, by 2010; 1 gigapixel, by 2020.

The service laboratories have a special role in the execution of DARPA programs. As agents for DARPA-led initiatives, the Army, Navy, and Air Force laboratories ensure that service S&T priorities are known to DARPA as it makes its investment decisions. Technical and program leadership by DARPA is central to meeting the DoD flat panel challenge.

1.2 DoD displays market

The military display market is being surveyed from within DoD by the Air Force Research Laboratory and from outside, by the Military and Avionics Working Group (MAUG) of the United States Displays Consortium (USDC). The technical report surveying some 370 weapon systems has been published in a restricted distribution report by Desjardins and Hopper [1] and in an unrestricted distribution summary paper by Hopper and Desjardins. [2] The USDC MAUG has issued its second draft roadmap analyzing the military and avionics market from the industrial perspective. Defense roadmaps are available.[3] These two efforts, one inside and one outside of DoD, enable a realistic view among all concerned parties of the definition of the niche market for avionic and military displays. The Optoelectronics Industry Development Association (OIDA) recently reviewed emerging commercial display applications and technologies and included a roadmap from the Japanese OITDA.[4]

* "FPD" is often used for all display technologies that reduce cost, weight, and space while increasing availability and performance.

1.3 DoD displays strategy

The DoD Director of Defense Research and Engineering (DDR&E) has endorsed a systematic analysis of technologies for their value-added in providing for the national defense. An example of such an analysis applied to displays as a core competency is illustrated in Figure 1. The method used is a quality function deployment approach with metrics. First, one states at the top left the payoffs from an operational perspective. Then the engineering goals, which if achieved will provide the opportunity to achieve the operational payoffs, are listed in the top right. Individual investments in particular science and technology projects are shown at the bottom. If a significant portion of the individual investments work out, the previously unattainable engineering goals become reality based on new technology, thus contributing to affordable national defense.

The DoD must leverage the trends in the civil commercial market. It is currently predicted that the FPD component market, serving applications from notebook computers to desk top monitors, will grow from the $25 billion share it held in 2000, to $50 billion by 2006, and will remain over 86% LCD-oriented. "Leapfrog" of AMLCD-commanded markets by FED anticipated in 1995 was not realized by 2000 as promised. Defense S&T programs must invest (1) in improvements needed in current technologies, like AMLCD, to meet advanced military-unique performance requirements, (2) in emerging technologies that may provide advantages over AMLCD (such as DMD and OLED) in some applications, and (3) in programs to revolutionize displays where military advantage is foreseen. Other emerging commercial markets, such as mobile communication and digital television, have strong implications for display industry components and will provide leveraging opportunities for DoD based on new commercially viable FPD technologies. Key DoD display programs than have ensured U.S. technology lead and prepared infrastructure for the industry base serving defense needs are summarized in Table I.

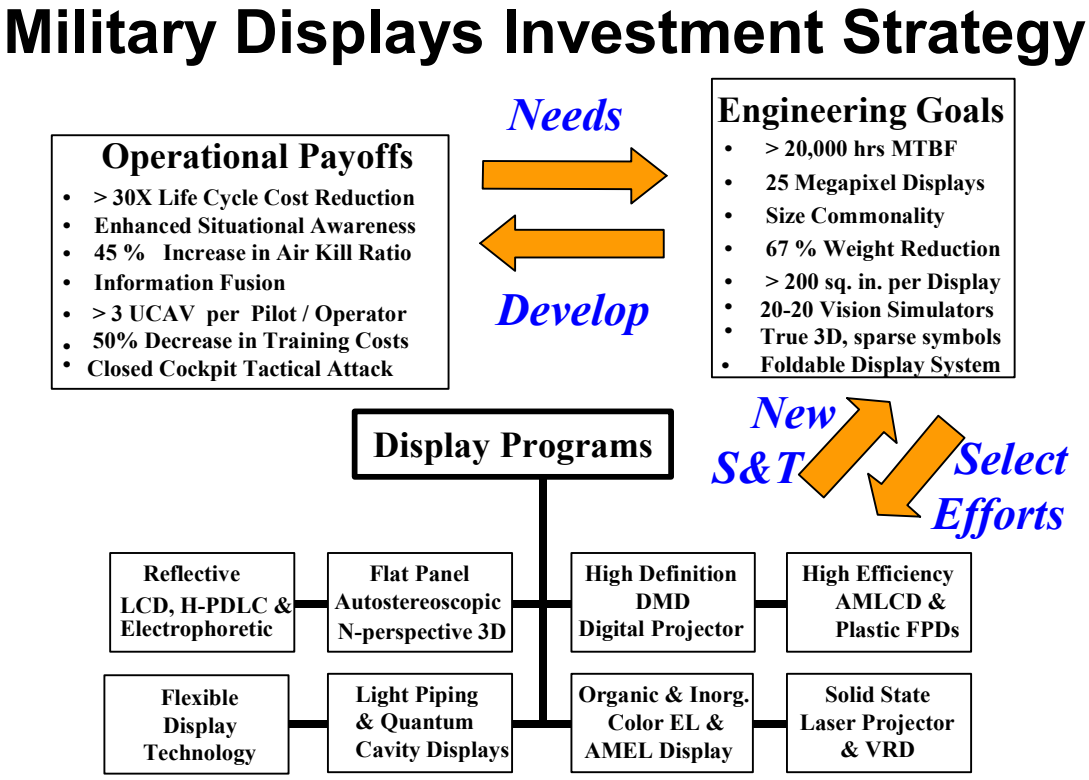

Figure 1. DoD technology investment and transition strategy applied to display science and technology.

Table I. DoD display programs to ensure technology lead and prepare infrastructure for U.S. display industry.

Program*	Acronym	Years*	Purpose
DARPA High Definition Display Systems and Related Programs:			
High Definition Systems **	HDS	FY89-FY01	Create new display technology
Head-Mounted Display Systems ***	HMDS	FY93-FY97	Demonstrate HMDs in field
United States Displays Consortium ****	USDC	FY93-FY01	Mfg. supply chain development
Advanced Information Component Manufacturing	AICM	FY93	Access DoE labs expertise
Phosphor Technology Center of Excellence	PTCOE	FY94-FY98	Establish phosphor research
Thin-Film Transistor Teams (part of HDS)	TFT Teams	FY94-FY99	Team academia with industry
Flexible Displays (part of HDS) *****	FD	FY99-FY01	Create FD, roll-to-roll mfg.tech.
AMLCD Pilot Demonstration Facilities (Manufacturing Technology Testbeds) Funded by DARPA HDS:			
AMLCD Manufacturing Technology #	AMLCDMT	FY93-FY94	Manufacturing testbed (OIS)
High Density AMLCD Mfg Technology #	HDAMLCD	FY94-FY95	Testbed (Xerox/Standish/ATT)
EL and FED Manufacturing Technology Efforts Funded by DARPA Technology Reinvestment Project (TRP):			
Active Matrix Elecroluminescent (inorganic)	AMEL	FY94-FY97	Dev. advanced EL (Planar)
Field Emission Display (notebooks) ##	FED (CA)	FY94-FY97	U.S. IP (Candescent)
Field Emission Display (cockpits, mobile users) ##	FED (MA/AZ)	FY94-FY97	French IP (Raytheon/Motorola)
Efforts Funded via DoD Agencies Other than DARPA			
Field Emission Display (notebooks, Abrams) ##	FED (ID/MI)	FY97-FY01	US/French IP (Micron/Pixtech)
Defense Production Act (Title III) for AMLCD #	DPA "Title III"	FY94 & FY96	Domestic capacity (AMLCD)
National Information Display Laboratory	NIDL	FY90-present	Display evaluation for C4ISR
Display Performance and Evaluation Laboratory	DPEL	FY00-FY01	Crewstation concept evaluation
Virtual Retinal Display	VRD	FY99-FY01	HMD for simulators, other
Micro-Organic Light -Emitting Diode	μOLED	FY99-FY01	HMD for fast-jet pilots, other
Panoramic Night Vision Goggle	PNVG	FY99-FY03	Increase FOV from 40º to 100º
Common Command and Decision Support System	DSS	FY98-FY08	Accurate combat team decisions
Ultrahigh Resolution Projector for Simulators	URPS	FY99-FY00	21-megapixel projection display
3-D Monitor (see-through, sparse graphical display)	3DM	FY00-FY01	Training mission brief/debrief
Digital Intelligence Situation Mapboard	DISM	FY00-FY01	Handheld digital electronic map
National Information Mapping Agency Viewer	NIMA Viewer	FY00-FY01	Soft-copy digital hi-res. Maps
Low Power HMD Displays	LPD	FY00-FY04	Low power HMD for soldiers
Strike Helmet 21 ATD Technologies	SH21 Techs.	FY01-FY04	Grd attack HMD fast-jet pilot
25-megapixel 2D and True 3D Display Technology	25M & T3D	FY02-FY06	New service thrusts

* Name of the program to which Congress appropriated funding. Years in which funding was appropriated or is planned.
** Known as the High Definition Television (HDTV) and High Definition Display Technology (HDDT) in FY1989
*** Initiated under the HDS program but funded with separate appropriations FY94-98.
**** High Definition Display Manufacturing Consortium BAA winner chose name United States Displays Consortium.
***** HDS program focused on flexible display technology creation, especially based on OLED, from 1999-2001.
# AMLCDs are preferred for cockpits, dominate notebook computers, now moving in to other markets (monitors, TV).
FED technology proponents claimed in 1995 that by 2000 some 20% of the notebook computer market would use FEDs; as of April 2001 no FED whatsoever has succeeded in any military application or in any commercial market.

2. DARPA DISPLAY TECHNOLOGY PROGRAMS

2.1 Goals

The armed forces Joint Vision 2010 emphasizes information superiority and increased situation awareness to secure strategic, operational and tactical military advantage while saving lives and reducing material losses. Information Technology consists of five fundamental processes: Acquisition, Processing, Telemetry, Assurance, and Display. While all of the five areas are essential, military Information Display is especially critical since it enables the human-system interface, increasing the effectiveness and lethality of over 350 military platforms to preserve our National Security. The mission of the Defense Advanced Research Project Agency (DARPA) is to maintain technology superiority and to actively transition DARPA-funded technologies into specific military applications.

The historical, strategic goal of the DARPA High Definition Systems (HDS) Program was to meet the diverse, but specific, Department of Defense needs for military displays. Displays often control information assimilation, impacting the speed and effectiveness of decision making - the ultimate test of display quality. The specific display related goals of the HDS program included increasing power efficiency, reducing weight, and improving the overall ruggedness of display systems, while pushing the state-of-the-art in display performance, or the ability to improve information assimilation.

Consistent with past efforts by DARPA to enhance US display technology leadership, the Flexible Emissive Display Program, initiated in 1999, intends to develop and demonstrate large area, high resolution, flexible, rugged, emissive displays for DoD applications. The focus has been on emerging organic light emitting diode (OLED) technology. These displays, which can be made flexible or conformable on substrates other than glass, are intended to address demanding display performance requirements of some military systems.

2.2 Funding

The display funding profile over the past decade is illustrated in Figure 2. The HDS program can be divided into four phases during these years. These phases include: (1) the HDTV years; (2) the innovative technology years; (3) the manufacturing years; and (4) the dual use years. The HDS program per se peaked in FY91 at $75M and fell off to $38M by FY01. Manufacturing display technology spending was managed by DARPA in conjunction with HDS per Congressional direction; overall display funding peaked in FY93 through FY96 due to several forward funded manufacturing technology (MT) programs whose execution ended from 1998-2000. Six manufacturing testbed facilities were funded for three different FPD technologies: AMLCD (two facilities), FED (three facilities), and inorganic EL (one facility).

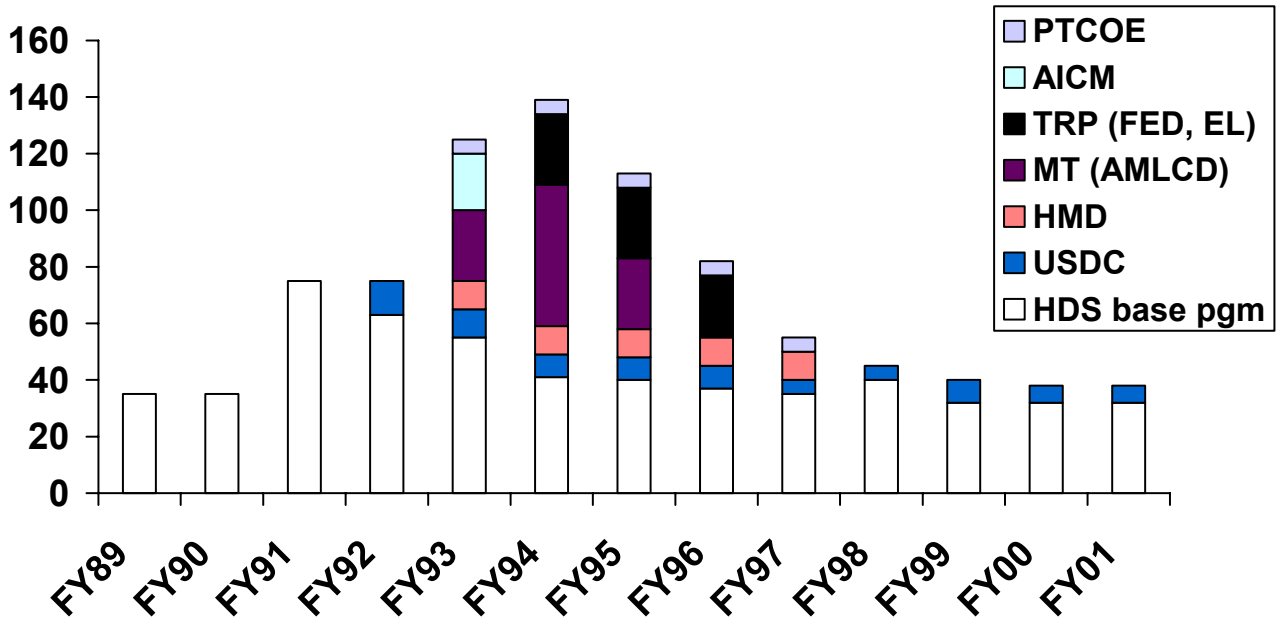

Figure 2. Darpa display funding profile for federal fiscal years 1989 through 2001. Acronyms: See Table I.

2.3 HDS program successes and failures

The HDS program has had several technology base and infrastructure development successes over the past several years. A few of the highlights are listed in Table II. Narrative descriptions of both successes and failures are provided below.

Table II. Examples of military programs enabled by DARPA display technology investments.

Technology	Application	Service	Program
TI DMD	Mission Crewstation	Air Force	Common Large Area Display Set for AWACS, JSTARS
		Navy	UYQ-70 shipboard and E-2C airborne
		Army	Common Hardware Software program for mobile C2
AMLCD Pilot Production	Aircraft Cockpits	Air Force	F-22 EMD, Op.Sys.Dev. for C-141C, F-16, et cetera
		Navy	F/A-18E/F EMD program and LRIP production lots
		Army	AH-64D EMD program and LRIP production lots
TFEL	Tank & Aircraft Ckpts	Army	M1A2 SEP (FLIR display) (upgrade from CRT)
		Air Force	Radar Warning Display (upgrade from green CRT)
Miniature	Helicopter HMD	Army	RAH-66 EMD (miniature AMLCD)
	Soldier HMD	Army	Demonstration for Land Warrior (miniature EL,i.e. AMEL)
	Fixed wing a/c HMD	Air Force, Navy	Tactical Fighter JHMCS EMD (miniature OLED DUAP)

2.3.1 Technology creation successes

The crown jewel of the HDS program is the Texas Instruments (TI) digital micromirror device (DMD) technology, developed in an $11.3M research effort managed by the Air Force Research Laboratory from 1991-1995. A 100% digital high definition system prototype was built—the only DARPA program to achieve the original HDS objective. The DARPA program reduced the risk to the point that TI management invested over $200M to commercialize the technology under the name "Digital Light Processing (DLP)" for the presentation projector market with the initial VGA product introduced in 1996 and SXGA, in 2000; the HDTV product, with full 1920x1080 resolution, is to be introduced when the HDTV market merits. Meanwhile, SXGA resolution is supporting the transition of DMD into the digital cinema and monitor markets. Transition to military programs began in 1996 with the development by TI of a military business plan addressing the dim-ambient workstation market to replace the 19-in. CRT common in mission crewstations in several C4ISR aircraft, including AWACS, JSTARS, and Airborne Command, Control, and Communications (ABCCC). The $12M Air Force Common Large Area Display Set (CLADS) program led by the Air Force Warner-Robins Air Logistics Center completed development and made its first production award in August 1999 for AWACS to Raytheon (which purchased the TI DMD military business about 1998) using DMD monitors manufactured by Texas Instruments near Dallas TX. CLADS is a performance specification: It is technology independent, it is vendor independent, it deals with legacy integration issues with a pathway to future digital display requirements. The CLADS model performance specification showed the potential for DoD to build a small family of 8 to 12 of common display sizes across platforms and services. The DMD technology has since been adopted by the Navy for AN/UYQ-70 workstations and is being explored by the Army for mobile command and control workstations.

Kent State University developed a 120 dots-per-inch (dpi), 220 x 280 mm (8.5 x 11 in.) reflective liquid crystal display that can maintain static images without consuming power. This display is based on the cholesteric liquid crystal technology, and is especially suitable for portable, low power applications. Kent State University is currently working on a color version of the display, as well as the technology required to use plastic substrates. In 1997 Kent entered into a display integration program with Honeywell to develop a "Zero Power" document viewer that would use wide color gamut bistable displays. The image in the display remains resident making this an extremely low power system. It supports a

program for the U.S. Army Military Police (MP) as part of their information management system. As a result of the capability the Kent display system provides, an Operational Requirement Document (ORD) has been drafted at the U.S. Army MP School to include this in the MP Automated Communication System (MPACS). Additional details on reflective displays are provided below in the discussion of reflective technologies.

The helmet mounted display (HMD) advanced development program originated as a component of the HDS program and has been an early demonstration vehicle for insertion of miniature flat panel displays in a variety of service applications such as maintenance, dismounted soldiers, and pilotage. Head-mounted display requirements include an ultra-strong dose of human factors engineering and are the subject of a separate conference proceedings volume edited by Lewandowski, Hayworth and Girolamo. [5]

From 1992 to 1996 Kopin Corp. developed and successfully demonstrated monochrome 1-in. AMLCD microdisplays with 24 μm pixels that supported ground vehicle, helicopter aircraft, and dismounted soldier head mounted displays with funding won via several DARPA solicitations (BAA91-06, BAA93-19, BAA94-04). These early developments caused the development of many microdisplay enabling technologies, such as active matrix backplanes, new lithography capabilities, filters for color for color displays, backlights, and interface electronics. Kopin then undertook development of 2000 pixel/in. microdisplays and demonstrated 2560 x 2048 pixel monochrome resolution in a 1-inch format with 12 μm pixels.

A key transition success of the HMD program is now underway for the Army's new reconnaissance/attack helicopter, the RAH-66 Comanche, which is now in its EMD system phase. In 1998 the Army picked the Kopin miniature AMLCD as the primary technology candidate for the helmet display system for the RAH-66 EMD program; the backup technology is the virtual retinal display (VRD), funded by Congressional plus-up money. For the RAH-66 program Kopin developed a monochrome 25-mm miniature AMLCD with 15 μm pixels (1280 x 1024 pixel resolution) based on combined additional funding of $7.4M ($2.66M DARPA HDS in FY98-99 with $4.74M of Army 6.3 funding in FY98-FY01). During FY02 the Comanche HMD system integrator, Honeywell, is to complete engineering activity to have the helmet system ready for flight tests by the beginning in FY03.

Kopin recently undertook a feasibility study for color microdisplays (800 x 600 and 1280 x 1024 pixel resolution) for the Land Warrior and the RAH –66 Comanche systems engineering development programs.

2.3.2 High definition display manufacturing consortium

The United States Display Consortium (USDC) was established as a DARPA/industry joint initiative in 1993 to give industry a voice and to provide leadership with regard to developing display manufacturing equipment, processes and materials needed to create a US-based manufacturing capability for the various display technologies being supported by DARPA. From FY1993 through FY2000 USDC awarded some $175M of U.S. display infrastructure projects of which just 39%, or $68M was provided via the DARPA HDS program. Since its inception, the USDC has initiated 70 development projects, of which 40 have been completed successfully and 22 are still under an active development contract. Some 25 of these projects led to the commercialization of new tools or materials needed for the fabrication of LCD, EL, plasma, FED, OLED and/or projection display systems. The USDC has also been active in working on manufacturing and display product standards, benchmarking of best practices, and establishing technology and product roadmaps for the different FPD technologies used in both military and commercial applications. Recent efforts focus on a common life cycle cost model for display acquisitions and manufacturing technology and materials for flexible displays.

2.3.3 Manufacturing technology pilot demonstration facilities

A total of six pilot demonstration facilities were built to develop manufacturing technology for three different types of FPD: AMLCD (two facilities), FED (three facilities), and inorganic EL (one facility).

AMLCD manufacturing technology facilities. Two facilities were funded via DARPA to provide a supply of U.S. manufactured active matrix liquid crystal displays (AMLCD) for U.S. military-unique applications—especially aircraft cockpits. Neither of the U.S. AMLCD manufacturing facilities, one at OIS and the other at Xerox (now dpiX), succeeded in developing a non-defense customer base and ceased production in August 1998 and March 2001, respectively. However, the DoD received a significant return on its investment the OIS and Xerox avionics AMLCD facilities during the period of their operation, 1995-2001. Without these avionics AMLCD pilot demonstration facilities several top priority

aircraft programs could not have gone forward during the 1990s. Examples include the engineering and manufacturing development (EMD) phase for the next generation U.S. Air Force F-22A Raptor air superiority fighter, EMD program and initial production of the U.S. Navy F/A-18E/F Super Hornet multi-role fighter, and EMD and initial production of the upgraded U.S. Army AH-64D Apache Longbow attack helicopter. Currently, combat avionics AMLCDs are manufactured in high volume facilities in Korea and Taiwan (military unique, custom designs), with dual use avionics AMLCDs in Korea, Taiwan, and Japan (Japan will only participate dual use, custom designs). Avionics AMLCDs are still all custom design albeit manufactured at opportunity cost in high volume facilities. Such facilities did not exist during the early-mid 1990s outside of Japan and the Japanese companies, which both then and now refuse to work military-unique programs like F-22, F-18, and AH-64. The Korean and Taiwanese companies now exist and will work with military-unique programs.

Four inorganic FPD manufacturing technology development facilities were funded via DARPA. Three were proposed and funded via the DARPA-managed defense conversion effort known as the Technology Reinvestment Project (TRP): one for inorganic electroluminesent (EL) at Planar; and two for inorganic phosphor FED (also known as "flat CRT"). A third FED facility was funded separately from TRP.

FED manufacturing technology facilities. Of the three separate field emission display (FED) programs, two were funded under the TRP and one as a Congressional interest program via DARPA and, especially, the Army Tank-automotive and Armament Command (TACOM). A team lead by Motorola and Raytheon attempted to develop the FED technology invented by Meyer et al. at the Laboratorie d'Electronique de Technologie et d'Instrumentation (LETI) and PixTech in France, and at its U.S. subsidiary, PixTech; this effort ended without delivering any useful products to market. Raytheon attempted to develop a high luminance FEDs, suitable for aircraft cockpits, but failed. The FED program led by Candescent pursued the goal of developing low-cost manufacturing technology for FEDs based on high voltage inorganic phosphors; the outcome of this investment is yet to be seen. The Congressional-interest FED program initiated by Micron Displays in 1997 was continued by Pixtech, which purchased the Micron Displays facility in Idaho in 1999; some $40M over FY97-FY01 (99% via TACOM plus-up) has been invested to develop 12-in. XGA prototypes for evaluation (the Army wants 10-in. displays and presently uses a ruggedized AMLCD for the map display). These three FED programs have yet to produce anything needed by any defense development or acquisition program. More importantly, there are as yet no successful commercial products based on FED technology. The investment in FED manufacturing technology may have been too early—it is now clear that much fundamental materials and device design work remains to be done before FED can hope to become a technology alternative to AMLCD. Nature had more tricks up her sleeve in 1995 than proponent companies were able to foresee.

EL manufacturing technology facility. A $60M TRP investment to a consortium led jointly by Planar and Allied Signal (now Honeywell) developed the process technology for low-cost agile manufacturing technology for inorganic EL technology over the period Oct 97 – Dec 99. Both monochrome and color efforts were simultaneously pursued. From a systems perspective the program had two components: (a) low-voltage thin film electroluminescent (TFEL) with passive matrix drive electronics for large area instrument panel applications and (b) miniature devices with active matrix electroluminescent (AMEL) electronics for HMD applications. The contractor teaming arrangement required individual partner members to be inter-operative with several or all members of the consortium. Based on the level of required interactivity between the consortium members, the TRP consortium, which was 50/50 cost shared by Government and Consortia partners, was a virtual corporation whose overall responsibility was to synergistically define the process control monitoring methodology for consortium. This TRP for EL was awarded a four-year option valued at over $60M; it developed manufacturing processes for 24 and 12-micron AMEL displays and refined processes for color and monochrome TFEL display technologies. In 2000, the Army awarded an analog dual use technology development for color displays and has established a manufacturing technology (Army ManTech) program to develop the process technology for these analog devices for Land Warrior developments. There are several head-mounted and head-up display applications that are attempting to use monochrome green AMEL miniature displays that were developed, or improved, under the Planar-led TRP effort, including demonstrations for Land Warrior and symbol-overlay in pilot night-vision systems. Also, the Planar-led TRP effort produced large area passive matrix driven thin film electroluminescent (TFEL) displays now in production for the 9-in. FLIR display in the Abrams M1A2 System Enhancement Program (SEP) and in development for consideration for the technology update of the 3-in. radar warning receiver display common to many fixed-wing aircraft.

2.4 Future display technologies of interest

2.4.1 Flexible displays

The DARPA HDS program focused on "legacy" technologies some of which, namely AMLCD and DMD and TFEL, now dominate the commercial world. There are currently several HDS programs, nearing completion, to develop the required, fundamental technology to use very thin substrates based on both metal foils and plastic.

The Flexible Emissive Display Program focuses on "transition" display technologies, which are now embraced as emerging technologies in the commercial world. These materials are compatible with low temperature processing, consistent with plastic substrates, characterized by lighter weight and improved ruggedness. Flexible displays would be useful for many applications including formed displays for cockpit applications as well as "window-shade" displays for command and control applications.

The distributed battlefield of the service visions for future systems—Army Objective Force, Future Naval Capabilities, Air Force Global Strike— will require visualization of web-centric information that must be conveniently available to Commanders on platforms as well as to the dismounted soldier. In addition, smart weaponry needs to be augmented with digital display capabilities.

Intelligent displays integrated into "smart sensor webs" will reduce the huge information burden (bandwidth reduction and filtration) that develops in a battlefield and can yield specialized, adaptive information. Embedding intelligence into high resolution displays will require applied, multidisciplinary research leading to functionally flexible displays for a wide range of applications, such as communication, friend/foe identification, and real-time distributed, situation awareness (SA) in the battlefield.

The ability to gather select information from many nodes of a distributed battlefield net and perform highly parallelized selective information processing will impart a new level of situation awareness to our warriors. Digital Devices on Demand will range from hand-held and helmet-mounted displays for the dismounted warrior and pilots, to those on moving platforms, mobile flight simulators, and in command and control centers.

Mobility is an essential element in the successful execution of many military missions. Therefore, display technologies, which enhance these capabilities and provide critical SA information, are a priority of the services and the DARPA programs. The need is manifest for field systems providing true portability, low power operation, and viewability in dynamic lighting environments. Low cost, light weight, good contrast, and ruggedness are all essential features of any display technology attempting to fulfill these mobile, mission requirements. Fortunately, present trends in the development of FPD technologies are toward displays which are light weight, low-power, thin, and full color with higher resolution and increased information content.

2.4.2 Reflective technologies and potential applications

Reflective FPD technologies have demonstrated most of the essential characteristics of low power, light weight, and ruggedness. Reflective technologies have two inherent characteristics which make them ideal to meet these stringent requirements. No backlight is required and the contrast ratio remains relatively constant over a wide range of dynamic lighting conditions. Thus, critical issues associated with low power, light weight, and good contrast are automatically addressed by the inherent characteristics of reflective FPD technology. These issues, and ruggedness, may also be addressed by fabricating the reflective display using non-glass substrates, such as plastic or metal foil.

A major disadvantage of the reflective FPD technologies is the requirement to have an external light source for viewing. Twilight and night time operations may be restricted. Work on color balance will lead to technology to solve low-ambient readability problems. A potential solution for night viewing in some circumstances is the use of infrared reflecting displays, an infrared source, and night vision goggles.

The development of reflective display technology has taken several approaches to yield "electronic paper". One approach utilizes polymer dispersed liquid crystal (PDLC) and holographically formed PDLC (H-PDLC) materials with active matrix

thin film transistor (AM-TFT) drive schemes. The second approach is based on reflective LCDs. A third approach involves electrophoretic processes.

The primary advantages of the H-PDLC approach are video-rate operation, full color, lower cost, and lighter weight (elimination of the backlight) with very high pixel density. The primary disadvantages are higher fabrication costs and less power saving (AM-TFT drive scheme). The PDLC displays are limited to monochrome applications. A color capability with significant control of the color gamut is provided by using H-PDLC materials.

The LCD approach to reflective FPDs is to utilize polymer stabilized cholesteric texture (PSCT) and surface stabilized cholesteric texture (SSCT) liquid crystal materials with a passive drive scheme. This approach offers two structurally stable material phases (bi-stability), which eliminates the need to constantly update the display. Consequently, no power is required to maintain display information once written. The primary advantages of this approach are minimal cost (passive drive scheme), minimum power (elimination of backlight and limited display updates), light weight, and night vision capability with relatively high pixel density. The primary disadvantages are slower update rates (material response and complex drive circuitry) and lower contrast (passive drive scheme); this approach is not capable of video-rate operation. This approach also provides a full color display potential, but with significantly less control of the color gamut.

The electrophoretic approach involves the controlled movement of reflective particles within a microcapsule, revealing or concealing a colored material.

Potential applications include avionics, ship, and land-based vehicular display systems, portable maps, and global positioning system (GPS) compatible navigation systems, mobile communications and data link interfaces, strategic planning systems, and hand-held procedure and survival manuals. Specific applications to support ground combatants include chart readers, portable field radios, hand-held GPS receiver units, and night vision systems. Specific applications to support air and sea combatants include avionics navigation units, radios, flight line maintenance computers, clocks, electronic technical manuals, flight landing template units, checklists, and conning tower remote bridge cases.

2.4.3 Emerging emissive technologies and potential applications

In addition to existing technologies such as AMLCD, Organic Light Emitting Diodes (OLEDS) have emerged as an exciting new technology that is making rapid progress as it nears widespread commercialization. The technology has evolved along two approaches: thin film polymers and thin film small molecules. Theoretically, OLEDS have an inherent potential advantage of low cost fabrication of monolithic, solid state devices via roll-to-roll coating processes onto a variety of substrates, including plastic. Also, many defense applications might greatly benefit from a transition from glass to plastic substrates in that less packaging weight and volume would be needed to protect against breakage. The development of effective plastic barriers to water and oxygen as well as effective encapsulation processes is key to implementing this technology into lower-weight, rugged, flexible displays.

3. AIR FORCE DISPLAY RESEARCH

3.1 Aerospace display vision

The Air Force Displays Vision is illustrated in Figure 3 in the form of goals for increasing situational awareness (SA) with time. The vision is based on the definition of two new classes of SA: panoramic, or 4-6 megapixels and immersive or 35-210 megapixels. These goals may be met by various combinations of direct-view and projection-view displays, depending on the specific application. The technologies necessary to build panoramic displays are emerging now and are a necessary step towards immersive displays. The number of pixels in these SA goals derives from 20-20 vision and the instantaneously viewable field of view: 120 x 60° or more for panoramic and 3π steradian or more for immersive (e.g. bubble-canopy fighter pilot field-of-view, simulators, advanced C4ISR command suites). [6] The basis for identifying the panoramic SA goal comprises such factors as the excitation of peripheral vision cues for horizontal viewing fields greater that about 100 degrees and the opportunity to present integrated display formats and/or to permit several pages to be simultaneously in view without cycling through menus. The basis for identifying the immersive SA goal is the necessity to plan for synthetic vision (a) to replace the view thorough the bubble canopy during conditions in which that view may not be available, such as bad weather, night, and laser threat, (b) to create realistic simulators for pilot training, skills maintenance/expansion, and mission rehearsal, (c) advanced operator stations for uninhabited vehicles designed, variously, for both ISR and combat missions); and full wall and room display systems for command and control rooms. [7,8,9] The Air Force Displays Vision is based on the observation that flat panel flight display resolution increases an order of magnitude about every seven years. Thus, increased from 28 Kpixels per display in 1987 to 410 Kpixels in 1994, to over 2 megapixels for development programs beginning after 2000. Extrapolation of this trend suggests another order of magnitude increase to 35 megapixels or more by 2010. [5] Higher resolution display systems with 10-100X more pixels than individual display devices are realized via tiling.

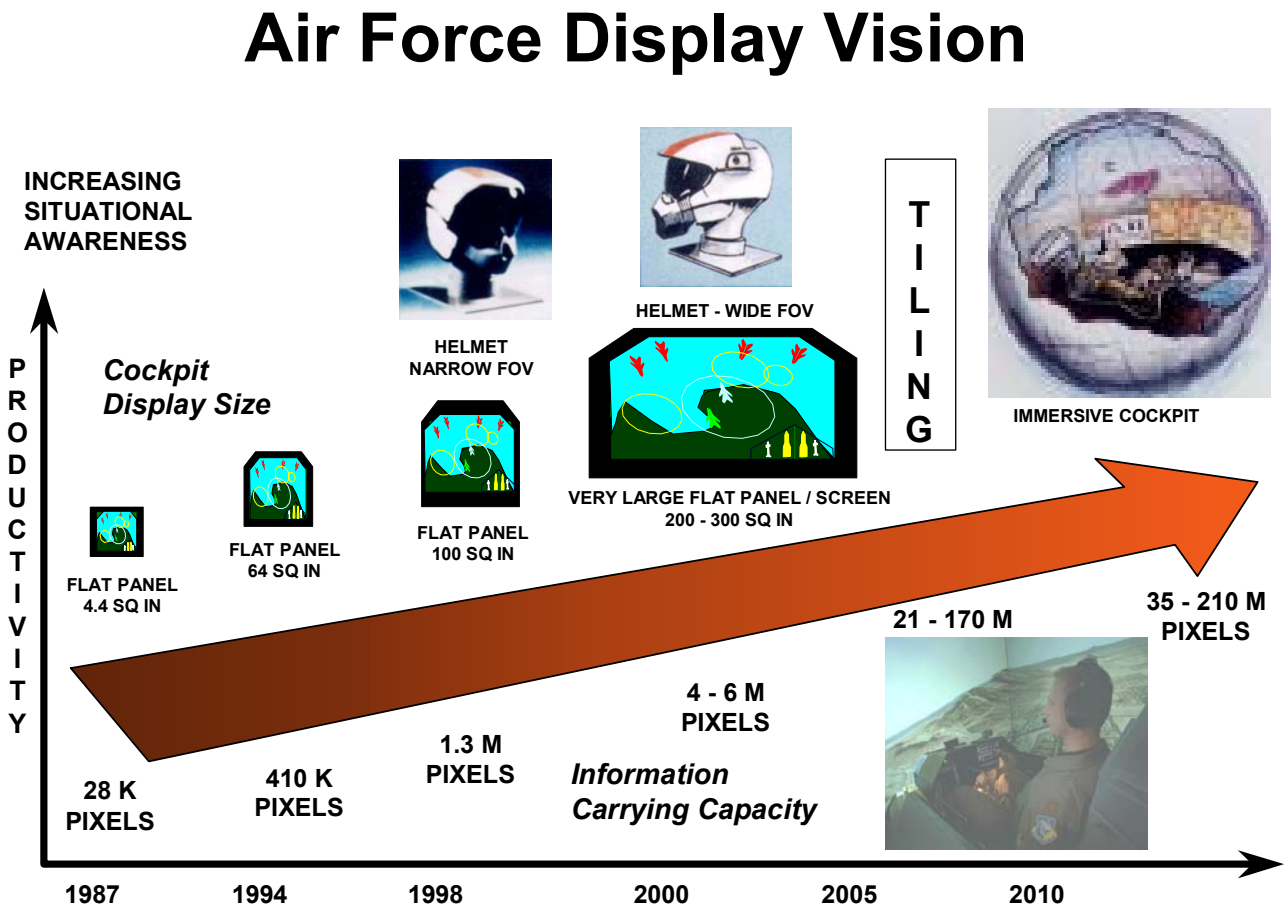

Figure 3. Air Force display vision.

Human 20-20 vision is 50 arcseconds subtended at the eye per resolvable pixel of text, and 0.5 arcminute, per resolvable pixel in images (such as 8-bit FLIR). A full, 4π steradian, field-of-view (FOV) requires approximately $(21{,}600\ n)^2 / 2$ pixels, where n is the number of pixels per arcminute. Thus, the resolvable number of pixels is about 233 Mpixels (text only) to 933 Mpixels (imagery only). The 210 Mpixel upper limit for the immersive cockpit derives from consideration that just a 2π-3π steradian FOV is available and that a mixture of low, medium and high resolution will be required for textual, graphics, and imagery. [5, 10]

Displays for a variety of fielded head, vehicle and wall mounted applications in tri-service human system interfaces can be addressed by the same display technologies required to make the AF vision a reality.

Prior to having the new display technologies robust enough and compact enough to work the integration into an airborne cockpit, other critical DoD applications can be addressed including mission crewstations for C4I and air traffic control, wall display systems for command and control rooms, synthetic vision systems for all applications, battlelabs and SimAF for virtual system design and demonstration without building a flying test aircraft, high definition trainers so that curricula can be taken further on the ground, and compact 1 m cubed (6 x 6 x 6 ft.) fully self-contained simulators for mission rehearsal and flight skill maintenance wherever an air wing is deployed and aboard carriers. The newer, more effective, trainers and simulators will become more necessary throughout DoD as fuel budgets shrink.

3.2 Air Force S&T Displays Program Overview

The Air Force science and technology strategy for displays encompasses all warrior-system interfaces needed to provide air and space global vigilance, reach and power. This strategy leverages world-wide private-sector display research investments to the maximum extent possible and cooperates with programs in all other government agencies. The strategy includes a consideration of system test, evaluation, acquisition, training, operations, maintenance, and life cycle cost during each research project. The service funded programs in display technology are focused on service-unique products, such as displays for combat environments, air/space-borne military sensor systems, simulators/trainers, and command centers. Frequently, however, a demonstration by one service has immediate payoffs in the others, as in combat cockpit displays in (air-/land-/amphibious-craft avionics/vetronics) and in crew workstation displays across all platforms. Thus, the Air Force participates in the DoD technology Reliance process to share its results and expertise with other agencies and to learn from their S&T investments. Air Force expertise supports the DARPA display technology creation program, provides a consulting service to acquisition programs in all services, and the OSD development of a defense-wide strategy for displays.

The Air Force is funding projects to improve the optical efficiency of AMLCDs and to develop a 5ATI * prototype flight instrument justified for aircraft cockpit applications. [11] Small Business Innovative Research (SBIR) Phase II awards have been made in resonant cavity quantum well display prototype [12] Helmet mounted display (HMD) applications in aerospace systems are being extensively explored both in-house and extramurally, including a recently completed SBIR funded project to create and develop miniature AMOLED displays and panoramic 100° night vision goggles (with image inset via microdisplay to overlay symbology of FLIR video) for head-mounted systems. Head tracker accuracy and latency requirements have not been met despite years of effort, and new technology is required. Complete audio visual environments (CAVE's) are being constructed to explore immersive interfaces. [13] In-house work is also underway in cockpit concepts based on a dynamic interaction of human factors and avionics; examples are human factors-derived requirements for FPDs and a true-3D approach to providing an effective threat warning display based on holovideo technology.[14,15] The creation of the CAVE and holovideo technologies also involved significant co-investment by DARPA.

3.3 Requirements

Warrior display research for aerospace systems is guided by the defense-wide concept of Global Reconnaissance Strike. Tri-service aircraft and spacecraft requirements may be further categorized into cockpits, mission crewstations, maintenance, survival kits, simulator/trainer systems, and command and control rooms. More detailed S&T needs and deficiencies flow from the analysis of both future and aging system performance specifications—which tend to grow over time. The life cycle for electronics in fielded systems is about 15 years; various systems are always undergoing technology insertion programs. The aging system technology insertion process is particularly important to maintain current operational capability as well as to gain the dramatically better performance and to realize the far lower ownership costs enabled by new flat panel display technology. Integration of current technologies in displays, sensors, and processors is needed to create a revolution in military affairs in terms of multimedia, real-time-to-warfighter information systems. Systems presently not envisioned commercially need to be prototyped over the next decade to prepare for Space Force and Air Force of 2025.

3.3.1 Aerospace cockpits

Aircraft cockpit displays involve a wide array of system types and individual systems, such as:

Fighter: F-22A Raptor, F/A-18E/F Super Hornet, F-117A Nighthawk upgrade, F-16C/D Fighting Falcon upgrade, Joint Strike Fighter (JSF, USAF/Marines/Navy)
Trainer: T-38C Talon Avionics Upgrade Program, T-45 Goshawk Cockpit 21, Joint Primary Aircraft Training System (JPATS, USAF and Navy)
Helicopter: AH-64D Apache, RAH-66 Comanche, MH-53J, SH-60R, CH-46 LEP, Rotorcraft Pilots Associate ATD
Bomber: B-52H Stratofortress ("Buff"), B-1B Lancer, B-2A Spirit technology upgrades and enhancements
Transport/Tanker: C-141B Starlifter, C-130E Hercules modifications, C-130H, C-130J, KC-135 Stratotanker, C-5B Galaxy, C-17A Globemaster III flight deck upgrade, C/H V-22 Osprey (SOF, Marines,AF,Navy)
Reconnaissance: RC-135, U-2, SR-71, EP-3
Space: Space Shuttle, Space Station, X-33, Space Liveboat, Maintenance Spaceship, Space Plane, and Space Fighter

Currently operational tri-service platforms (bombers, helicopters, tanks, trucks) that must be operated on or near the surface at night based on imagery from a FLIR or LLLTV all tend to require a 254 mm (10 in.) monochrome green display with 256 levels of gray. The B-52 and B-1 programs evaluated four technologies to replace the 230 mm (9 in.) CRTs used to view FLIR/LLLTV terrain imagery during low level flight: AMLCD, EL, plasma, and the Polyplanar Optic Display (POD). Cockpit display replacement programs almost always select color AMLCD (large direct-view or miniature projection- view) regardless of the other technologies considered during development.

Air Force aging aircraft upgrades affording opportunities for display technology insertion include the following weapons systems requirements: A-10 Advanced Cockpit, C-130 Integrated real-time-in-the-cockpit (RTIC) capability, Predator uninhabited air vehicle (UAV) Tactical Control Station, and KC-135 RTIC capability, and B-2 Central Information Display (CID) for Link-16 communications.

Mission crewstations are typically positioned in a dim-ambient environment and are ruggedized versions of commercial technology.

3.3.2 Advanced command and control centers

Wall display systems with > 100 megapixels and true-3D monitors are both unavailable yet required by users for future C2. Productivity in currently operational C2 rooms must rise while crew sizes shrink: better displays will enable this miracle.

3.4 Opportunity-driven display technology needs: panoramic and immersive

Panoramic and immersive display systems are noted above in the vision section. Improved display technologies are needed for simulators, trainers, UCAV, and command centers. CAVE-like human system interfaces with 5-20 Mpixels will be necessary over the next few years to extend training curricula and mission rehearsal capabilities further on the ground prior to burning jet fuel. Also, programs like SimAF to design next generation aerospace weapon systems digitally without a prototype fly-off competition will require brighter, sharper, ultra-high resolution display systems with 10-100 times as many pixels as in present day simulators. DoD battlelabs will require the same technologies, as will anchor desks for integrated situational awareness for battle staff.

Panoramic cockpits are just now becoming possible, as shown in Table III. Current sensors, let along those in R&D, cannot be shown on the small displays on the F-22 or other fielded aircraft. A display at least 15 in. across is required for current sensors; the largest display in the F-22 is 8 in. across.[16] Real-time-in-cockpit implementations need even more additional display area and resolution. For example, current 4 megapixel images cannot be shown to pilots as current cockpits have just 0.4 megapixels or less in a single display surface. True panoramic cockpits will require FOV greater than 100°.

Immersive displays are those that can provide the user with a field of view with some 1 billion pixels (1 gigapixel). A concept of such a system is illustrated in Figure 4. This concept is representative of the need for higher resolution synthetic vision systems for simulator/trainer systems in the near-mid term and advanced cockpits in the far term. Such large area, curved display systems will require the flexible display technology just now being created by DARPA.

Table III. State of the art fighter cockpit versus potential next generation designs (to be fielded during next 10 years).

System	No. Displays	Different Sizes	Total Area	Total Resolution	Advantage
F-22A Raptor	6	3	0.129 sq.m (201 sq.in.)	1.35 Mpixels	Baseline
RPA Adv. Tech. Demo.	3	1 (less logistics)	0.137 sq.m (211 sq.in.)	2.36 Mpixels	2X more info.
JSF breadboard	2	1	0.103 sq.m (160 sq. in.)	2 or 3 Mpixels	Seamless, 33°

Figure 4. Gigapixel cockpit concept (operational in ground systems by 2015, in air and space craft by 2025).

3.5 Deficiency-driven display technology needs

Deficiencies exist in the areas of custom size large displays required for cockpit instrument panels, rear-screen projection systems for use in cockpits, limited field of view of cockpit displays compared to current sensors, miniature flat panel display to replace miniature cathode ray tubes in helmet-mounted display systems, panoramic night vision goggles, training vision systems, synthetic 2-D and true 3-D vision systems for both training and for command and control suites.

A new technique know variously as AMLCD re-sizing, or cutting, needs to be developed as an alternative method of providing the custom size displays needed in many aerospace cockpits and other defense applications. Presently custom manufacture is mandatory for volumes of just a few hundred each—affordability is a critical issue here. Rectangular 4:3 aspect ratio commercial displays can be cut to the 1:1 form factor needed in most cockpits. For example, the F-22A requires an 8x8 in. image area display—no other application on earth (neither military nor civil) needs this size, yet DoD needs just 339 plus spares. Avionics displays are not a good business deal for the industry unless the quantity of flight instruments is at least 1,000.

Separately, the AMLCD cutting techniques may enable higher fill factors in instrument panels, thereby enriching the informational interface to aerospace systems pilots and operators. For example, trapezoidal display shapes can be produced. The aerodynamic and space constraints on cockpit design for combat aircraft and land combat crew stations produces odd-shaped instrument panels which heretofore could not be filled with high information content displays. The DARPA flexible displays program is providing an additional opportunity to deal with such confined space applications.

Rear-screen projection designs are now being developed for both dim-ambient C4ISR crewstations and sunlight-readable aircraft cockpits. These projection applications provide systems risk in the form of the light source, light engine, and screen. More efficient light sources are required (improved arc lamps, invention of solid state light sources). Screens affect the quality of the image provided to warfighters compared to direct view AMLCD—better screens for sunlight readable applications and human factors research are needed to support F-22A and F-/A-18E/F plans to move some one display size in each cockpit to the LCoS projection design by 2003. The LCoS technology has yet to be proven commercially viable (a mandatory maturation step for a display technology to be used in weapon systems).

Miniature AMOLEDs are needed to replace miniature CRTs for fighter pilot helmet systems. A significant effort is needed to mature and ruggedize the monochrome green 15-micrometer device and to develop multi-color versions—at several resolutions (800x600 up to 1980x1024 pixels).

Panoramic night vision goggles now in advanced development provide fields-of-regard up to 100° but need to be less in their weight, volume, and power requirements. Also, these image intensifier devices need to be integrated with several miniature flat panel displays for symbol overlay and/or synthetic image insertion from sensors or computers.

Brighter and higher resolution projection displays are needed for simulator/trainer synthetic vision systems. The current systems are so low in luminance (just 12 nits compared to 500 nits needed) and resolution (20/200 acuity presented compared to pilot/trainee visual acuity of 20/10) that the training or mission rehearsal is not realistic. Better electronic display device technology is the number one technology deficiency for the defense-wide simulator community. [17]

Generals and admirals for decision support systems in command and control rooms have requested true 3-D displays. They want to see the eyes and body motion of remote team members as if they were in the next seat. Separately, they want to have multi-person, auto stereoscopic (*nothing* on the head, they insist) monitors that intuitively depict the 3-relationship of objects in a volume of air, water, or space around both the battle area and their platforms.

3.6 Air Force Science and Technology organization for displays

Air Force display research is located in the Human Effectiveness Directorate, Air Force Research Laboratory. The Crew Station Integration Division at Wright-Patterson AFB OH is the center of excellence for aerospace display technologies.

4. ARMY DISPLAY RESRESEARCH

4.1 Army display vision

In order to understand the Army vision for displays and display technology one first has to consider the type of force that the Army wants to be. This vision of the future is shown in Figure 5. The vision consists of the Legacy and Interim Forces that will transform into the Objective Force. The vision for displays in the Army is to support this transformation. Therefore, the display technology and systems must support the Legacy Force as it maintains and improves its capabilities and it must equip the Interim Force with new and improved display technology. Both of these goals combined with innovative basic and applied research on materials and structures will lead to technology demonstrations that will help the Objective Force to be: Responsive, Deployable, Agile, Versatile, Lethal, Survivable, and Sustainable. What this means for displays may be seen in Figure 6. The key S&T program for achieving the Objective Force is the Future Combat System (FCS). Note that the soldier is the centerpiece of the concept. The displays required for this vision may be called out as the dismounted soldiers HMD, which links him to the information from all the other pieces of the combat system, both direct view and HMDs for pilots, drivers, and combat vehicles as well as displays for immersive environments.

4.2 Army S&T Displays Program

4.2.1 Overview

The overall development of technology falls under the purview of the Assistant Secretary of the Army (Acquisition, Logistics, and Technology). The Assistant Secretary of the Army (Acquisition, Logistics, and Technology), ASA(ALT), serves, when delegated, as the Army Acquisition Executive, the Senior Procurement Executive, the Science Advisor to the Secretary, and as the senior research and development official for the Department of the Army. The Deputy Assistant Secretary for Research and Technology (SALL-ZT) has the responsibility for the Science and Technology Master Plan (ASTMP). The "*Army Science and Technology Master Plan* " (ASTMP), annually revised and approved by the Secretary of the Army and the Army's Chief of Staff, provides Department of the Army guidance to all Army Science and Technology (S&T) organizations. As such, it is the strategic link between Department of Defense technology planning and the plans of Army major commands, major subordinate commands, and laboratories. This plan for the Army's S&T program is based on the Army leadership's vision of the future Army and available resources." [18]

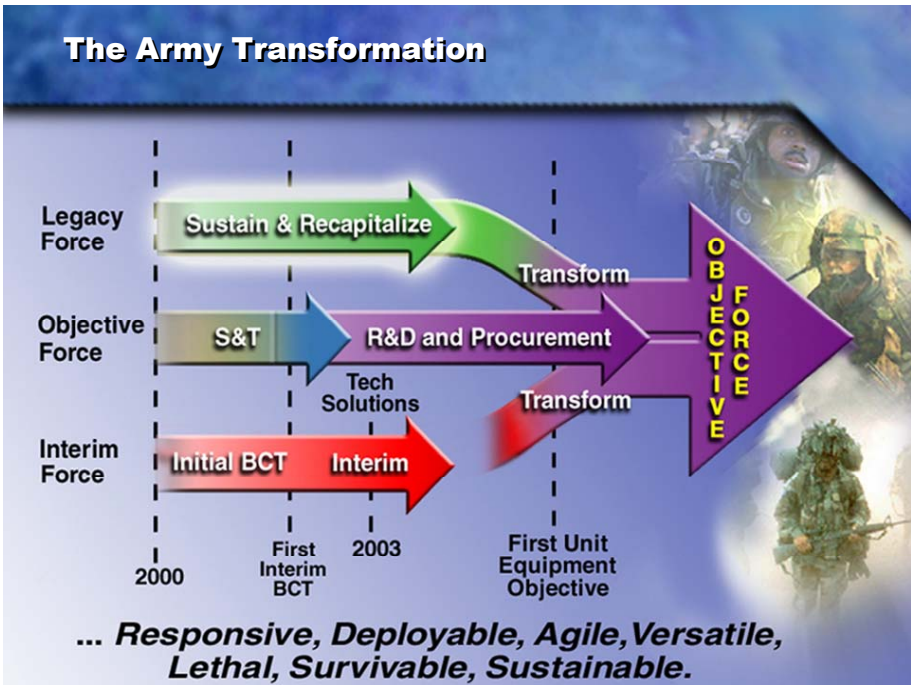

Figure 5. Timeline for Army Transformation into the Objective Force.

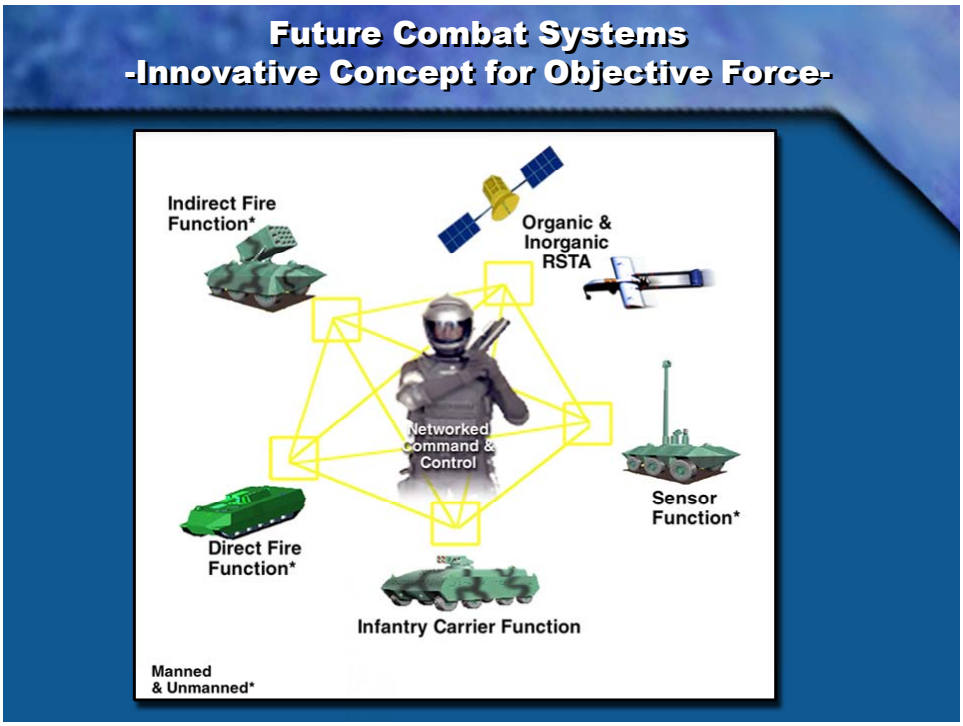

Figure 6. Future Combat Systems concept for the Objective Force. Ref: LTG Kerns, Briefing (approved for use)

The Army S&T program is executed severally by the various Research, Development, & Engineering Centers (RDECs), Program Executive Offices and Program Managers (PEO-PMs), and the Army Materiel Command (AMC), which includes the Army Research Laboratory headquartered in Adelphi MD. The AMC vision is: "A recognized world leader in adopting, adapting, developing and applying the key affordable and innovative technologies required to transform the Army into a force that is strategically responsive and dominant at every point on the spectrum of operations." [19]

The structure of R&D for displays for the Army has evolved over the last decade. Close ties to the Army user community and other DoD agencies (Air Force, DARPA, Navy) have always been maintained. The latest change in the organization was to bring the Army sponsored very basic academic research managed by the Army Research Office (ARO) into the Army Research Laboratory, while keeping it physically at Research Triangle Park NC. Historically this element reported directly to AMC. The current R&D organization is shown in Figure 7.

Until the early 1990's the Army Electronics Technology and Devices Laboratory (ET&DL) was located at Ft Monmouth NJ with the Communications and Electronics Command (CECOM) and led display research for the Army ranging from basic research to display development to test and measurement. In about 1996 ETDL was reorganized into the Army Research Laboratory. The structure for the research and development for displays was changed so that ARL had the mission for basic materials and device research for future display technology and for supporting the RDECs through technology program annexes (TPAs). The ARL was consolidated under a base realignment and closing (BRAC) move into two main sites at Adelphi and Aberdeen, both in Maryland. New laboratory facilities were constructed at both sites.

This current research relationship is show in Figure 7. Thus, the Army display program covers the spectrum from basic research to technology insertion. With the changes in organization described above, ARL is the focal point display research in the Army. Under the ARL banner, the technology directorates and ARO perform basic and applied research in coordination and collaboration with the RDECs, the other services, industry, and universities. RDECs beyond CECOM include the Tank-automotive and Armament Command (TACOM) in Warren MI, the Soldier, Biological & Chemical Systems Command (SBCCOM) in Natick MA, the Aviation and Missile Command (AMCOM) in Huntsville AL, and the Strike Command (STRICOM).

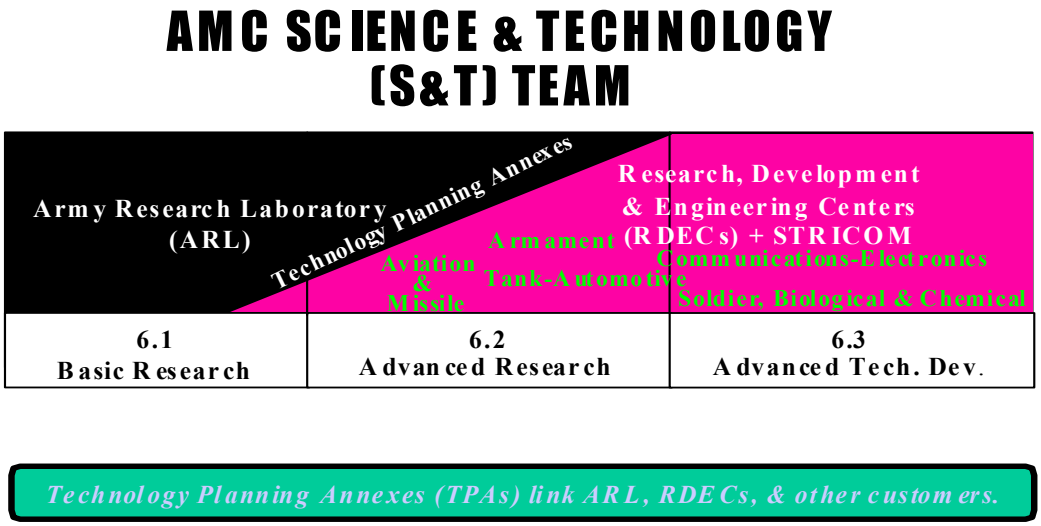

Figure 7. Army Material Command (AMC) science and technology team.

4.2.2 S&T Examples: ARL display research

ARO is the ARL organizational unit which manages much of the directly funded 6.1 basic research at universities. The ARO program is organized along scientific disciplinary lines as benefits basic materials work. ARO sponsors single researcher programs at different universities as well as Multidisciplinary Research Initiatives (MURI). An example of the basic work funded at a single University is the "Optically Written Displays Based on the Up-conversion of Near Infrared Light" at the University of Central Florida. The MURI program belongs to the basic research office at the Office of the Director of Defense Research and Engineering with service XRO's like ARO as agents; these programs are 3-5 years with several universities using their individual expertise to work toward a single goal in a collaborative manner. Typically, MURI programs have a scientific liaison with the ARL directorates and the other services to assist in program formulation and direction. This ensures the research is directed toward Army and other Service system development needs and provides a path to the RDECS for technology demonstration. Currently there is an approved MURI for "Intelligent Luminescence for Communication, Display and Identification". This program will directly support the Army S&T for displays by providing the basic materials and devices for new display technologies The objective of MURI is the development of the underlying fundamental interdisciplinary science supporting intelligent forms of luminescence, including inorganic and organic based materials. Another related MURI is "The Atomic Cluster-derived Materials (ACM)" Project. These programs are a piece of the basic research foundation for Army display technology.

The ARL Sensors and Electron Devices Directorate (SEDD) has responsibility for doing basic research and applied research for displays. The display team resides in the Electro-Optics Division of SEDD. This group has three objectives: (1) conduct basic research on luminescent materials and devices; (2) partner with the RDECs to develop technology demonstrations, and (3) provide assistance to Army users. In order to accomplish these objectives a center for the luminescent materials and devices (displays) research has been established at the Adelphi MD site of ARL. The capabilities of this facility include a wide range of thin-film deposition techniques and processing as well as a wide array electro-optical, spectroscopic, and analysis tools. Some of these capabilities are shown in Figure 8. In addition to the facilities assigned to the display team per se, the extensive capabilities of ARL may be brought to bear as required. The most critical example for materials research is the SEDD physical analysis capability.

Figure 8. Army Research Laboratory facility for luminescent materials and devices.

The internal research done by the display team at ARL concentrates on materials and devices that appear to have application to Army systems and where ARL's work may impact the technology. Two of the current areas of interest are organic and inorganic electroluminescence, Figure 9 illustrates several of the basic device structures.

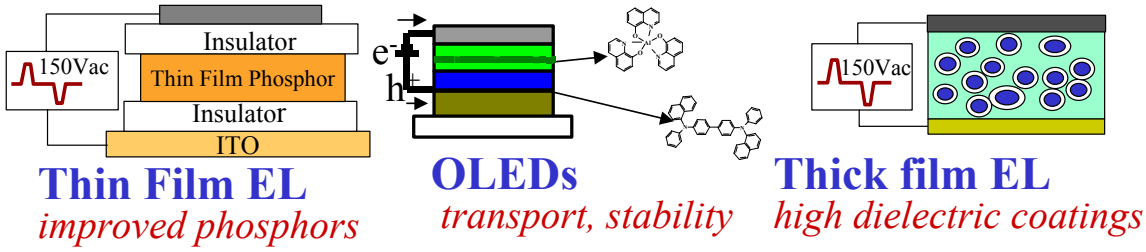

Figure 9. Schematic drawings of basic structures for inorganic and organic electroluminescent (EL) devices.

The ARL work in these technologies illustrates the team effort of display research in the Army. ARL is focusing on novel materials and structures for both inorganic and organic EL technologies as well as helping with the general understanding of the physics of these devices. [20,21,22,23] The ARL research on conduction and defect states in these materials has contributed to the development of these technologies for Army systems. Recently, we utilized these defect spectroscopy's to identify the origin of temperature instabilities in metal sulfide based devices. These materials are the basis for inorganic EL displays from Planar Systems used in the M1 tank program. [24] In addition, these unique spectroscopies are supporting the organic based display community in the identification of carrier transport limitations. In general, the ARL display

team works closely with contractors for SBCCOM and DARPA who are developing technology demonstrations as well as with several universities. Thus, much of ARL research is directly applicable to display technology development. ARL provides a range of research support to the RDEC and DARPA contractors that span material and process development to analysis and prototype evaluation. ARL is now supporting four DARPA/RDEC contractors in the flexible display program by providing thin film deposition, physical analysis, surface morphology, optical evaluation and process information.

An example of collaboration between the RDECs, DARPA, and ARL is the successful TRP program for inorganic EL displays (program managed by SBCCOM, prime contractor Planar Systems) which lead to the development of HMD display a demonstration for Land Warrior and direct view displays for the Commanders Independent Thermal Imager in the M1 tank, as described above in the DARPA section of this paper.

Another aspect of the Army display research is the "Display Performance and Environmental Laboratory" Program at the Microelectronics Center of North Carolina (MCNC). The program is being managed by ARL SEDD, which is coordinating the effort with the other nationally funded display laboratories, such as the National Information Display Laboratory (NIDL) hosted by Sarnoff Corp. in Princeton NJ for the Navy and the Display Test and Evaluation Laboratory within Air Force Research Laboratory at Wright-Patterson AFB OH. The MCNC program is being focused to investigate the basic materials issues, which are limiting factors in the development of display technologies that may be important to DoD. The initial emphasis of the program will be on technology that is applicable to flexible displays, but the scope will include any display material or technology that is of interest to the Army and DoD. MCNC will also investigate novel optical techniques in microstructure measurement, analysis of viewing optics, and seamless tiling of displays. MCNC will participate in display standard committees to address Army and DoD needs in commercial market.

4.3 Requirements

The requirements for future display technology come from the Army's Battle laboratories. The Battle laboratories were created in response to the factors and implications of a changing world, strategy, budgetary reality, and a need for a new way of doing business. The mission of these Army Battle laboratories is to identify future operational capabilities (FOCs) by working with the Training and Doctrine Command (TRADOC), AMC, and the Army Corps of Engineers). These FOCs provide a description, in operational terms, of the capabilities required in the past, present, and future. The FOCs are used to develop the Army Science and Technology Objectives (STOs) and the TRADOC science and technology (S&T) reviews, and to construct Army Advanced Technology Demonstrations (ATDs). The FOCs are also used to assess the relevance of Advanced Concepts and Technology II (ACT II) topics, and of the proposals received against the ACTII BAA.

The followings FOCs and ATDs from the current Army Science and Technology Master Plan address display capabilities. These capabilities require a wide range of displays that allow the soldier easy access to information anywhere on the battlefield.

FOCs:

TR97–005, Airspace Management.
TR97–015, Common Terrain Portrayal.
TR97–017, Information Display
TR97–056, Synthetic Environment.

ATDs:

Rotorcraft Pilot' s Associate (RPA) ATD.
Advanced Helicopter Pilotage PhaseI/II.
SubsystemTechnology for Affordability and Supportability (STAS).
Low-Cost Aviator' s Imaging Multispectral Modular Sensors
Tactical Intelligence Data Fusion
Advanced Electronics for Future Combat System (FCS)
Force XXI Land Warrior (FXXILW)
Cognitive engineering of the Digital Battlefield

5. NAVY DISPLAY RESEARCH

5.1 Military mission

Navy mission goals require a wide variety of FPDs. Hand-held electronic maps for navigational aids, body-worn displays for Marine Corps and paratrooper applications, electronic manuals for submarines, sunlight readable displays for on-board and field applications, high resolution, high pixel density displays for situational awareness are examples of the display needs of the Navy. A typical example of a display that is needed for the operational requirement of the Marine Corps is the need for a flexible & curved display that can be wrapped around the body of warfare fighter who is dropped by a parachute into hostile territory. A body-worn display using which the situational awareness is continuously monitored is an essential requirement of such a situation. For submarine applications, any reduction of weight is a very important factor. Repair and maintenance manuals contribute a major part towards the weight factor of a submarine. Plastic, portable displays that do not require a computer but which carry thousands of pages of information (including maps) on a small chip mounted directly in the display will become electronic repair/manuals that can replace the usual paper manuals. Large area plastic displays for camouflage requirements are also important for field-applications. High sensitivity uncooled IR sensing displays are important for anti-sniper warfare applications.

Several current S&T programs, many of them sponsored under DARPA programs, are being tailored to meet the above-mentioned Navy requirements.

5.2 Display Technologies

Navy display technology efforts involve the development of novel materials as well as display devices to meet the Navy, DoD and commercial needs. Considerable efforts are underway in the development of plastic, flexible LCDs. These efforts include the development of processable, optically transparent, conducting polymers, liquid crystal alignment layers suitable for plastic substrates, novel liquid crystal materials and dielectric materials that are coated at low temperatures. The Naval Research Laboratory (NRL) and the Office of Naval Research (ONR) in collaboration with Kent Displays Inc jointly developed world's first fully multiplexed plastic LCD. The Navy has also funded, through SBIR programs, industries like Kent Displays Inc. to develop reflective cholesteric displays using the conducting polymer technology developed at NRL. This effort has resulted in demonstration of a monochrome, full VGA (640x480), fully multiplexed, plastic display with built-in electronics, as illustrated in see Figure 10. More recently a three-color plastic display has also been demonstrated. Efforts are underway to develop plastic-based OLEDs in collaboration with Uniax and other industries.

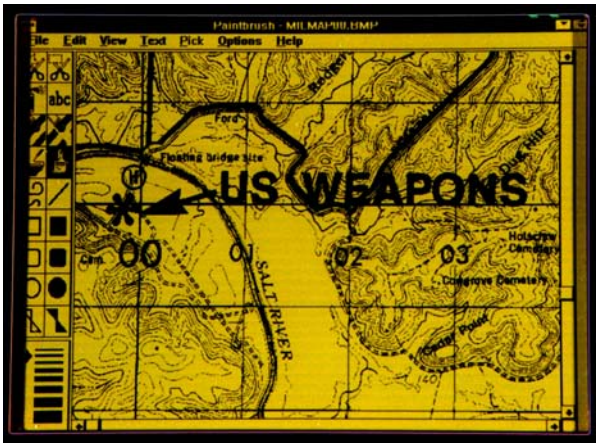

Figure 10. World's first fully multiplexed plastic liquid crystal display
Developed jointly by NRL and ONR in collaboration with Kent Displays Inc.

Navy has also pursued the development of ultra-fast, high-resolution displays. Working with industrial partners, NRL and NSWC have developed analog gray scale, fast switching displays that are adaptable for several applications like optical processing and target recognition, head-mounted displays and optical communication. ONR is working closely with NRL and industry (Kopin, Spatialight) towards insertion of the analog LCDs into Navy systems.

The Navy is also developing high sensitivity, uncooled IR sensing display devices based on pyroelectric properties of liquid crystals. When completed, these displays will have high sensitivity over a wide IR wavelength (3-10 μm) range and will be easily field-deployable. Another display technology that is being developed by the Navy is the acoustic imaging display. Such a display will have the capability to image objects in shallow and murky water. This works on the principle of optical imaging using ultrasonic waves and based on the sensitivity on a class of liquid crystal materials to acoustic waves. When completed, such a display will be inserted into a hand-held sonar imager that can be employed by a Navy diver for underwater mine hunting and mine recognition applications.

5.3 Reflective technologies and potential applications

In view of the low power requirement, ease of fabrication as well as direct reading capabilities of reflective displays, the Navy has focused on the development of two types of reflective displays – cholesteric reflective displays and liquid crystals on silicon (LCDs) display devices.

5.3.1 Cholesteric reflective displays

Reflective cholesteric (Ch)-LCDs are ideal for use in portable or hand-held held devices to display information such as maps, text, or graphics because they offer high resolution, sunlight readable images on a lightweight, low-power display. These desirable optical properties are a result of the unique features of cholesteric liquid crystals. When cholesteric liquid crystal material is confined between two closely spaced (on the order of 5 microns) substrates, it typically assumes the planar texture. In the planar texture, the liquid crystal director (the average orientation the liquid crystal molecules point at the region in space) rotates about an axis. For the perfect planar texture, all axes are oriented perpendicular to the substrates. The twisting of the liquid crystal director about these axes creates a continuously varying, but periodic dielectric permitivity. Because of this periodicity, the material will Bragg reflect light incident on the sample when the pitch (distance over which the director rotates 360°) is comparable to the wavelength of incident light. By applying an electric field to the cholesteric liquid crystal mixture, the material can be placed in the focal conic texture. In this state, the helical axes are oriented in random directions. The material ceases to reflect light and becomes transparent or weakly scattering depending on the material composition. By treating the bottom substrate with a black absorber or by using a dark conducting substrate, a pixel in the focal conic state appears black. Utilizing these developments, reflective Ch-LCDs have been made using glass substrates coated with the transparent metal ITO to apply an electric field to the material. Similar reflective displays have also been made on plastic using conducting polymer electrodes.

5.3.2 LCOS displays

The Navy has played a very important role in the development of high resolution, microdisplays that are reflective and do not use backlight. Industries like Microdisplays Inc., Spatial Light and Kopin (which have been separately funded under different DARPA programs) have worked with NRL and ONR in developing high resolution displays based on nematic (active matrix) and ferroelectric (passive-addressed) display devices. Such displays have already been integrated with projection displays and are being tested at several Navy system commands.

6. DISCUSSION

The DoD strategy of winning via information contains several challenges to make the impossible possible in display technology. First is the pixel challenge: Wherever in DoD operational units there are people and pixels, put more pixels and less people; where there are people but no pixels, put pixels. There arise immediately several sub-challenges, such as how to put high resolution display systems onto the heads of dismounted soldiers, aviators, maintenance and BM C4I SAR personnel. The curved display challenge involves developing non-flat but thin displays to wrap information around a confined crew space or virtual system design simulation and trainer systems. Synthetic vision systems are another grand challenge, including canopy display systems for use during adverse weather/laser conditions, remote immersive C4I, and battlelabs. The generation of content will require a several order of magnitude increase in the graphical rendering speed to achieve panoramic display generation (PDG) and, then, immersive display generation (IDG) in compact, energy efficient, fieldable form.

The sensors community is far ahead of the display community: displays need to catch up. Currently deployed FLIR imaging systems capture a 25° field of view but current cockpit displays (including F-22) are far too small to present the information to pilots. Research on next generation FLIR sensors is now at 25 megapixel resolution—display devices of comparable resolution do not exist. Similar examples exist for imagery from SAR, satellites, and decagigapixel digitized databases.

Investments made over the past decade have prepared the stage for display technology to proceed to meet the pixel challenge presented by the DoD information strategy. DoD investment emphasis since 1989 through 2001 is summarized in Table IV. Continued investment in new technology creation is strongly recommended by opportunities such as those identified throughout this paper to reduce DoD costs and increase capability. Infrastructure investments by industry may continue at a reduced level as this work should be picked up by industry subject to standard market forces. The stage is now set for additional emphasis on the transition into DoD applications of the nascent technologies arising from previous HDS investment. The new technologies selected for this transition emphasis may be primarily from among those that have already been transferred to civil commercial applications. Economic viability of the technologies selected for transition is critical, as weapon system life cycles are measured in decades and DoD will usually buy but a fraction of the production volume of even a niche market commercial plant. Transition programs will, per force, leverage commercial market trends.

In retrofit programs, LCC analyses routinely demonstrate the potential savings with a return-on-investment of 12:1 for non-recurring engineering, procurement, and installation of FPDs in system after system throughout DoD forces. However, these savings do nothing for current year acquisition budgets from which initial procurement price must be paid. Thus, there will be a continuing role for the DPA Title III program which has been used to reduce the risk to tri-service program offices of adopting FPDs in their retrofit and upgrade programs.

Entirely new S&T thrusts are needed in DoD by the Services to create technology for 25 megapixel display devices (tiled to achieve up to 900 megapixel display systems) and for true 3-D displays.

Table IV. Investment emphasis of DoD display programs over last and next decade.

Investment Emphasis	Initial Period for Funding	Status and Recommendation
HDS Era		
Technology	FY1989-2001	HDS program ended FY2001; developed display technology base for digital television
Infrastructure	FY1994-2001	Parts of HDS and DPA Title III; continue but with 100% industry funding
Post-HDS Era		
Maturation	FY2002-2007	Service programs to mature HDS technologies for transition to weapon systems
Transition	FY1996-2010	Service programs for mature technology transition (started during HDS with DMD)
S&T	FY2002-2009	New R&D initiatives such as 25-megapixel devices and true 3-D displays

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