High Resolution Displays and Roadmap *

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Abstract

Synthetic vision systems for artificial reality and tele-presence remain far short of the resolution of the human visual system. Current electronic display systems support 20/20 visual acuity or less, yet human vision is dramatically better than the 20/20 measure implies. Compelling applications and products will require ever more resolution, grayscale, etc. Current technology must grow from 1 megapixel devices common in the year 2000 to 10-100 megapixels devices by 2010-2020 to support, eventually, systems with aggregate resolution well over 1 gigapixel. A vision of displays for the next decade and century will be provided along with a roadmap for high resolution display devices.

Key Words: Electronic Displays, Synthetic Vision

1. Introduction

Artificial reality and tele-existence systems are limited by display technology. Advances in displays and digital television are now poised to enable a 10-to 100-fold growth in capability (e.g. resolution) by 2010. Such improved displays will pay for themselves via increased productivity in work, home, and entertainment applications. Simulators and trainers might leverage this digital display trend to produce synthetic vision systems at 20/20 resolution (170 megapixel needed versus 16 megapixel at present). Such 20/20 simulators could save fuel and increase safety by reducing training needed in real vehicles, increase the effectiveness of pre-mission rehearsal, and enable realistic human factors research. Uninhabited vehicle interfaces will require 10-100X more resolution just to keep up with advanced sensors (video at 25 megapixels per frame) and databases (100 megapixel portions of 8-30 gigapixel scientific and terrain domains). Knowledge walls and complete audio-visual environments (CAVEs) for control rooms and education will prepare the way for in-vehicle hectomegapixel display systems with 200 megapixels like the Ford 24/7 concept car. Entertainment applications include home IMAX. This paper reviews electronic display trends enabling synthetic vision concepts. A vision of displays over the next 10, 20, and 100 years is presented.

2. Synthetic Vision Concepts

Displays have crossed the megapixel threshold. The human visual system (HVS), however, is capable of processing one gigapixel color images of full motion video. A substantial closing this 1000X gap will dramatically increase productivity.

2.1 Need

The common "20/20" metric for visual acuity (i.e. 50 arc seconds subtended at the pupil) is defined for a room maintained at a very dim ambient illumination (e.g. 100 lx). In Nature the range of illumination is many orders of magnitude higher (0.01-108,000 lx). In the real world the luminance contrast is usually sufficient to resolve objects far less than 50 arc seconds. For example, stars in the night sky subtend perhaps as small as 5 arc seconds or less, yet people see stars. Similarly, glint from a highly reflective surface is readily visible, but often subtends < 20-25 arc second. Also, 20/20 is defined for black/white only and ignores color, 3D, and motion as image resolving features of human vision.[1]

Humans move in a 3D world with images arriving from all directions. These images are continually being integrated as one moves about and looks in any direction at will. Thus, an ideal display would cover the full 4? sr of a natural world scene; this solid angle is equivalent to over 1.3 billion two-dimensional picture elements (pixels). Adding a third dimension leads to volume element (voxel) resolutions up to 22 trillion voxels. Resolution comparisons for 4? sr are provided in Table I (pixels) and Table II (voxels).

It is true that human visual acuity in the foregoing discussion refers to an instantaneous attention angle of about 2 arc degrees. However, it is also true that this acuity (and far better, down to 0.5 arc second for verier acuity) actually exists in real world scenes over 4? sr. Also, the high rate of eye scan and head movement, combined with the sensitivity of peripheral vision to motion, requires full image be present continuously at full visual acuity over 4? sr, ideally, just as in Nature.

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Table I. Number of resolvable pixels in 4? steradians.

Acuity	Comment	Pixels
50 arc seconds	20/20 vision	213,860,000
25 arc seconds	Glint and	855,450,000
20 arc seconds	Stars *	1,336,700,000

* Real world luminance & chromaticity contrast effect.

Table II. Number of resolvable voxels in 4? sr.

Depth Layers	2D Acuity	Voxels (billions)
10	50 arc seconds	2
	20 arc seconds	13
100	50 arc seconds	21
	20 arc seconds	134
1000	50 arc seconds	214
	20 arc seconds	1,337
	5 arc seconds	21,386

* Holodeck of Starship Enterprise ? 1 trillion voxels.

High definition digital television will be but a first phase of efforts to close, somewhat, the gap between fielded displays and the HVS capability in Tables I and II. Business, entertainment, education, advertising, training, and other applications will drive the creation of rooms in which every surface (walls, furnishing) have embedded displays. Pixel rooms will take the form of walls covered entirely with flat panel displays (FPD); covering all walls creates a CAVE or FPD igloo for immersive systems. Also, vehicles—including cars, trains, and aircraft—often must be operated under conditions in which the outside world is not clearly visible due to conditions of night or bad weather. A view of nothing might be dramatically improved by providing larger area and synthetic vision display systems under these conditions.

2.2 Super-Panoramic Cockpit (SPC)

A program of studies conducted by the Air Force Research Laboratory has demonstrated the productivity improvements available when one begins to deal with the display technology challenge identified above. The approach in this program, entitled "Panoramic Cockpit Control and Display System (PCCADS)," is to provide a pilot with large area displays and a helmet-mounted off-axis target-acquisition weapon-targeting system. There were two projects, one focused near term, one far.[2]

The PCCADS 2000 cockpit was designed to be realizable with 1995 technology with production by 2000 and featured a 25 cm (10 in.) square tactical situation display and two 15 cm (6 in.) square secondary multifunction displays on either side. All displays were full color capable with a total area of 1110 cm^2 (172 in^2). The test mission was for an F-15E. A 28% increase in exchange ratio was achieved versus the standard F-15E cockpit. An 18% increase was observed for the addition of helmet cueing to the F-15E baseline cockpit. Coupling this large display with a helmet-mounted cueing system for off axis target acquisition resulted in a 45% increase. The F-22A Raptor will realize the PCCADS 2000 concept in a production cockpit (video wall comprising six flat panel AMLCDs with an aggregate resolution of 1.35 megapixels at 5-bit greyscale in 1290 cm^2 (201 in^2) plus an HMD add-on. Beyond the PCCADS 2000 cockpit was PCCADS.[2] PCCADS was designed to be realizable with beyond 2000 technology and featured a 2000 cm^2 (300 in^2) head down display system which appears seamless, but which, in fact, must be implemented in a physically redundant fashion to meet fail-soft and reliability requirements.

This PCCADS research demonstrated the payoff in increased situational awareness from integrating all information and displaying it to the pilot on one very large display format. The PCCADS cockpit, plus curved "wing" displays for improved man-machine interface and a closable inner curtain, is illustrated in Figure 1. This concept, the super-panoramic cockpit (SPC), has features which might be explored over the next 5-20 years to enable closed cockpit operations. A closable curtain gives way to a flexible canopy display in the far term. Stowable flat panel displays or projection screens are deployable either side of the head-up display.

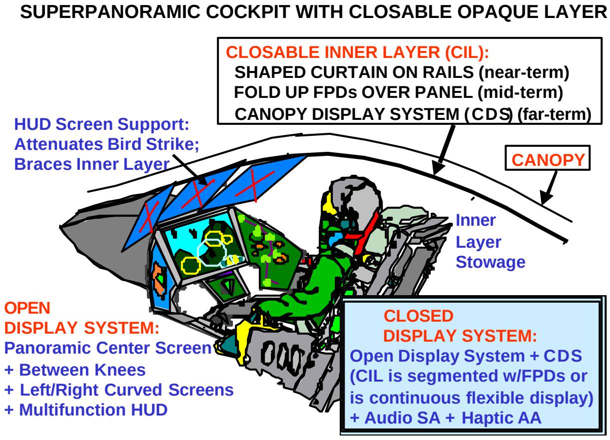


Figure 1. Super-panoramic cockpit (SPC) with closable curtain or flexible display, plus fold-up FPD screens.

2.3 Synthetic Vision Perspectives

There are two complementary approaches to the design of synthetic vision sysems: outside-looking-in (OLI) and inside-looking-out (ILO). In the OLI approach, the viewer perceives himself to be located outside looking in on the world presented on the display. In the ILO approach, the viewer perceives himself to be located inside the displayed world looking out at it. Large field of view, 120 x 60° or more, is required for one to "think" one is actually immersed in the world presented on the display(s). The ILO approach is achieved today by the real world itself as viewed via real immersion or real windows in vehicles. For aircraft the windows are often in the form of a transparent canopy: the pilot is centered in a real world with all display elements coming from real world phenomena. Today's fielded desktop and auto/cockpit head down displays (HDDs) represents the OLI approach. Significant development in display technology is required to implement either the large area OLI or, eventually, the ILO approach.

The head-mounted version of either the OLI or the ILO approach has yet to catch on despite the great hype. In all human applications people exhibit a strong, visceral aversion to head-mounted solutions. Even companies developing head mounted displays (HMD) to replace computer monitors and cell phone displays do not yet use their own product in their own office. This leads us to a rule that applies to HMDs:

Rule for Head-Mounted Equipment (HME):
People will wear HME only if they will die if they don't.

Soldiers wear helmets to decrease the chance of death. Individuals who must wear corrective lenses do so in order to live (e.g. drive cars safely) and many opt for contacts or laser eye surgery to remove the need to wear glasses. People will wear HMDs as a necessity or a novelty, if at all, and will ***not*** wear them *in lieu* of displays elsewhere (walls, television, computers, monitors, cell phones, personal digital assistants, etc.).

Different parts of the display system will employ small, medium and large area direct-view visual displays. Niche applications like military must leverage the commercial market to the maximal extent possible. The creation of a display technology, even after key inventions have been made, takes 3 to 20 years for manufacturing process development followed by integration and ruggedization for military applications.

Research directed at the creation of display technology required to support both the OLI and ILO approaches is reviewed in subsequent sections.

2.4 Cockpit Vision

Fieldable cockpit display technology in 2000 is represented by the B-777 commercial transport, F-22A fighter, and RAH-66 helicopter. Each pilot has 650-1300 cm^2 (100-200 in^2) comprising 2 to 6 color multifunction displays (MFD).

The cockpit vision in Figure 1 comprises a 4000 cm^2 (600 in^2) super-panoramic direct view head-down display (HDD) system coupled with a simple helmet display for off-boresight cueing of smart munitions. The HUD is still present as a ballistic munitions targeting reticule unambiguously and accurately aligned with the airframe. Deployable displays may be integrated either side of the HUD. The cockpit canopy may be turned opaque via a simple shade or a complex display shell. A world view is created in the closed cockpit mode from on-board/off-board digital data bases, the on-board sensor suite, and the off-board sensor suite.

The 2020 vision is an encapsulated cockpit as illustrated in Figure 2. The pilot may have no windows. The cabin may be a self-contained spheroid embedded within the aircraft or, possibly, elsewhere. This display system might be much like that of a present-day trainer/simulator—only far, far better. The system will be color and high resolution. The pilot has the option of retaining or selectively removing real world visual effects of weather and night. The 2020 vision includes actual views from not only ownship, but also from a variety of other platforms via cameras, data bases, and data links. The capsule is a node in a digital network.

Figure 2. Encapsulated cockpit realized as combination of direct-view, projection and head-mounted displays.

2.5 Display Vision

Our goal is to create a display technology base to enable the design of panoramic and immersive cockpits. The opportunity to do so arises from significant investments by both the commercial and government sectors "to make the impossible possible" for an ever-expanding global industry of visual digital applications. In this endeavor we are the beneficiaries of the information age and the insatiable market for better and more visual communication and entertainment devices. Our strategy is to pursue multiple technological approaches: revolutionary new display technologies, groupings (arrays,seamless tiling) of flat panel displays, and projectors. Haptic, auditory, and olfactory displays will also merit consideration. A vision for the evolution of displays is discussed in more detail by Hopper.[3]

2.6 Performance Specification

Visual displays must be readable in a variety of situations. Performance specifications range from detailed (dozens of parameters) to summary (3-4 aggregate metrics). Some key specifics follow.

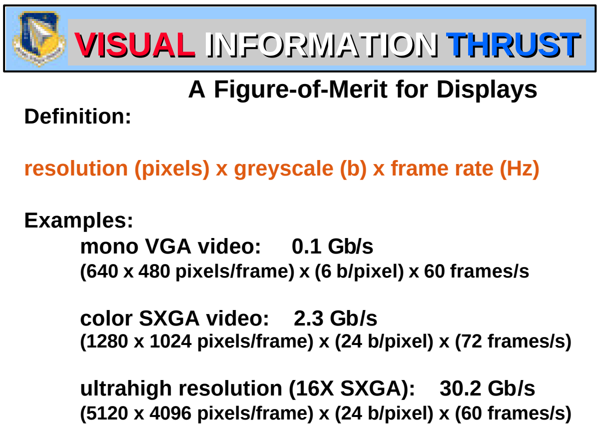
2.6.1 *Large area with high resolution*
Display module sizes must measure at least 25 cm (10 in) up to more than 150 cm (60 in) diagonal. Pixel densities for display screens places 60 cm (24 in.) from the viewer must be at least 32 cm^{-1} (80 in^{-1}) up to 100 cm^{-1} (240 in^{-1}). Several modules or sizes can be grouped together as necessary to achieve the total aggregate display area required up to e.g. 25 m (100 ft) for IMAX or NASDAQ.

2.6.2 *Sunlight readable*
Persons with normal vision must be able to read the display in both direct and occulting sunlight. In each case the sun is not attenuated. Direct sunlight means the sun shines on the display; occulting, into the viewer's eye. The goal inherent in this requirement is usually expressed in terms of the luminance (light intensity) emitted and contrast maintained by the display for a specified illumination condition. Full daylight is taken to be an illuminance of either (a) 108000 lx (10000 fc) directly incident on the display with luminance of 1710 cd m^{-2} (500 fL) incident at the specular angle with respect to the test viewing angle, or (b) 21500 lx (2000 fc) illuminance, with 6850 cd (2000 fL) luminance at specular. The contrast ratio must be at least 4.66:1 (5 grayshades) under the highest luminance condition and 10:1 under 40 % of the highest; the goal is 50:1 for all cases. These requirements translate, for example, to a display white field luminance in excess of 510 cd m^{-2} (150 fL)—which was the best CRTs ever did despite all human effort to do better. For video applications at least 750 cd m^{-2} (220 fL) is preferred so that 8 grayshades/color can be discerned. Some believe that over 3,400 cd m^{-2} (1000 fL) is required.

2.6.3 *Variable brightness, grayscale, night vision*
Viewers must be able to adjust the brightness to be viewable in a continuum of over six orders of magnitude of ambient illuminance from 108000 lx down to 0.11 lx (10000 fc to 0.01 fc). The electronics to accomplish this dimming ratio (0.01 to 1000 fL) is half the cost of a sunlight readable display. Eight colors (3 bits) often suffice for symbology; color graphics and video systems ideally require 48 bits. Military applications must be compatible with night vision systems.

2.6.4 *Environmental*
There are two enviromental aspects. First, new displays must take the impact on the environment into account: from the mining of raw materials, through manufacture, during use, and ending with disposal. Second, the conditions during use—temperature extremes, shock, vibration, humidity, electronic interference, dust, kicking, etc.—must be considered in display design.

2.6.5 *Aggregated Metrics*
Aggregate metrics are required to describe displays to communities of widely differing backgrounds. Such metrics include: life cycle cost (LCC) for several years of operation (e.g. 10 yr.); power efficiency in terms of efficacy in lm/W; and visual information thrust in Mb/s. Thus, LCC is needed to show a return on investment (ROI) of over 3:1 to justify investment; experience for cockpit FPDs is an ROI of 13:1, which justifies insertion of FPDs in place of electromechanical and cathode ray tube displays. Power efficiency is vital in all weight-sensitive applications. Visual information thrust (VIT) in bits/s was introduced by Hopper.[4] The definition of VIT with examples is provided in Figure 3.



VISUAL INFORMATION THRUST

A Figure-of-Merit for Displays

Definition:

resolution (pixels) x greyscale (b) x frame rate (Hz)

Examples:

mono VGA video: 0.1 Gb/s
(640 x 480 pixels/frame) x (6 b/pixel) x 60 frames/s

color SXGA video: 2.3 Gb/s
(1280 x 1024 pixels/frame) x (24 b/pixel) x (72 frames/s)

ultrahigh resolution (16X SXGA): 30.2 Gb/s
(5120 x 4096 pixels/frame) x (24 b/pixel) x (60 frames/s)

Figure 3. Visual Information Thrust: an aggregate metric of what a display is capable of providing.

3. Technological Approaches

Technological approaches to large area, panoramic, and immersive displays include array, tiling, and projection. Direct view arrays are known commercially by such names as video wall. Tiling retains several individual displays, but removes the spaces between them. Tiling can be accomplished by several methods: juxtiposition; circuit pasting; optical stitching (appears seamless). Flexible displays produced by roll-to-roll web processing may affordably provide seamless display screens of very large size in the far term. The status of display technology development was reviewed recently at the U.S. DoD Defense Advanced Research Projects Agency (DARPA) Information Exchange Conference on High Definition Systems.[5] Integration of display technology into aerospace and defense applications is documented in a series of widely available conference proceedings, comprising almost 3000 pages, published in seven volumes by the International Optical Engineering Society edited by Hopper.[6]

3.1 Direct View Displays

3.1.1 *Cathode tubes and electromechanical*
Avionic CRTs and electromechanical (EM) instruments have problems with reliability, availability, sunlight readability, and scalability. Also, CRTs and EM cannot be scaled to 2000 cm^2 and larger areas with space, weight, and power in most applications. Research in areas like flat-CRTs may provide new options, however.

3.1.2 *Flat Panel Active Matrix Liquid Crystal Display*
The active matrix liquid crystal display (AMLCD) is the only flat panel display technology currently capable of high brightness (sunlight readable) and full color. It is the preferred display technology for all applications. Research to invent the AMLCD began about 1969. The first commercial product successes—hand held TV and small cockpit displays—occurred about 1988 when the pixel density reached 80/in. Sizes range from 8 to 700 mm (0.25 to 30 in.). Tiled versions go up to 1m (40 in.).

3.1.3 *Flat panel: Thin-Film Electroluminescent*
Research started in 1994 has created an additional FPD technology for avionics and military applications that is sometimes a better choice than an AMLCD. The yellow thin-film electroluminescent (TFEL) passive matrix addressed FPD has been developed for monochrome video in sizes up to 20.3 x 11.4 cm (8 x 4.5 in.).

3.1.4 *Flat Panel: Field Emission Display (FED)*
A field emission display (FED) is another possibility. Performance demonstrated to date will ***not*** support applications. Flashover problems associated with high voltages (5-12 kV across a small gap of <1mm) have prevented success. The FED is still a technology in search of a birth date even after 8 years of strong effort.

3.1.5 *Flat Panel: Organic Light Emitting Diode*
Over the past five years yet another flat panel display technology has begun to appear in products: active matrix organic light emitting diode (AMOLED) display. Initial low information content applications are now available for car radios. Cell phones. digital assistants, cameras, and avionics versions are in development.

3.1.6 *Flexible Displays*
A revolution in display technology has begun. Displays fabricated on glass may eventually be replaced by displays fabricated from plastic. Substrates might be expanded to flexible thin sheets of steel. The dream of roll-up displays and less weight/power is being pursued. Research has demonstrated an ability to fabricate the thin-film transister (TFT) electronic circuitry for AMLCDs or AMOLEDs at process temperatures as low as 75 °C. A second approach to flexible displays is the "optical lattice" in which light is generated at the edge of the screen (infrared or visible) and piped via optical waveguide structures to pixels.

3.1.7 *Printable Displays*
Large, flexible, flat displays will require a second revolution: roll-to-roll (so-called "web" equipment, as in newspaper production) with cutting of desired displays sizes from the "cloth" produced in the display production line. In 1998 Polaroid successfully demonstrated roll-to-roll production of passive matrix liquid crystal display cells. Transition of other display technologies to web processing is underway.

3.2 Tiling

The vision for the fully immersable concept, such as Figure 2, will require a significant expansion of the current state of the art in display technology. A complementary alternative is to move the current discrete displays so close together that one perceives one large display rather than several discrete displays. In this way it becomes possible to present a seamless panoramic display across the tiled array yet retain physical redundancy to maintain reliability.

3.2.1 *Justapositioning.*
The individual displays could just be placed next to one another with the viewer tolerating the clearly visible gaps or seams. The 1990 state of the art was represented by the 6144 x 2048 pixel, 152 x 51 cm (60 x 20 in.) prototype built from three 2K x 2K color CRTs by at MIT. Air Force satellite constellation management uses seven of these CRTs, for a total resolution of 29 Mpixels. The NewsMuseum in Arlington VA has 90 VGA (640 x 480) projectors tiled on a wall, a total of 28 Mpixels. The Air Force Research Laboratory warfighter training team in Mesa AZ has produced a simulator using eight screens each rear projected by a 1600 x 1200 projector, a total resolution of 15 Mpixels. Seamless tiling by cutting AMLCD edges was shown in late 2000.

3.2.2 *Optical stitching*
Stitching involves optical means to make the physical display structure comprising the discrete displays appear to be one large display by optical schemes. One might imagine display tiles mounted on the back side of a display screen with each magnified optically to fill its portion of the big image seen by the viewer. Microlens arrays or holographic sheets might be used. Curved and wall filling displays having resolution of 10 Mpixels or more might be made in this fashion. Sarnoff Corp. is pursuing such an approach to multi-megapixel displays for immersive C4I and entertainment applications. The closable screen depicted inside of the transparent bubble canopy in Figure 1 becomes a segmented hard shell with displays in each portion. Macro-optical-coupling makes a segmented display array appear to be one large display. One macro-optical approach is to tessellate a spherical surface into areas the shape of pentagons and hexagons. Then a flat large FPD is projected a few inches to each polygon (curved sphere segment) via a space-filling fresnel optic. The viewer would see an apparently seamless, curved large solid angle display with a total resolution of the FPD used times the number of tessellation segments times a fill factor (a non-rectangular image inside a rectangular flat panel does not take up all of the addressable pixels).

4. Projection

There are several projection methods: cathode ray tube (CRT), liquid crystal light valve (LCLV), microelectromechanical (MEMS) devices, p-Si and x-Si miniature AMLCDs, and solid state laser display (SSLD). Projector light power output is given in watts at the aperture or ANSI lumens at the screen; one must specify a projection solid angle to compute luminance or a screen size to compute illuminance. More than 1 W per color leaving the projector aperture is required. The light source for all SLM-based projectors (MEMS, AMLCD) is presently an arc lamp; more compact, bright, power efficient, and reliable solid state sources are being developed (inorganic LEDs and visible solid state lasers). Screens also need improvement.

4.1 CRT and LCLV Projectors

Cathode ray tubes and light valves have been used in projectors for some time. The CRT displays are of much lower quality than the LCLV. An example is the Hughes Series 300 LCLV system, based on an optically written a-Si photoconductor, which projects 2500 lm at video rate with good contrast for a price of $150,000; additional limitations include low frame rates and thermal sensitivity. The resolution provided is so low that 20 foot high letters on a carrier tower cannot be read in a simulator—requiring the early curriculum transition to burning jet fuel.

4.2 MEMS Projectors

Microelectromechanical (MEMS) devices can be fabricated that serve as spatial light modulators (SLM) in a projector light engine of a visual display system.

4.2.1 *Digital Micromirror Device Projector*
The Texas Instruments digital micromirror device (DMD) presents a near term practical alternative to both direct view CRTs and other projection technologies for applications. A depth of about 10 in. behind the viewable screen surface is required. The prototype color high definition 1920 x 1080 pixel system (17 micron pixel pitch) incorporating three 3.2 x 1.9 cm (1.25 x 0.75 in.) DMD chips with a 16:9 aspect ratio, a 150:1 contrast ratio, and projecting >1000 lm to the screen was developed over the period 1990-1995. As of 1999 the TI "Digital Light Processing (DLP)" light engines based on the DMD have re-defined the state of the art in commercial presentation projector market.

4.2.2 *Defractive Grating Light Valve Projector*
The diffractive grating light valve (GLV) linear spatial light modulator being developed by Silicon Light Machines, Inc. (SLMI) is a different type of MEMS device. Light is modulated by micrograting diffraction pixels rather than by moving micromirror pixels. SLMI is currently attempting to tile four 1024 x 1 pixel devices and use scanning to develop projector with resolution of at 5120 x 4096 (21 Mpixels).

4.3 AMLCD Projectors

Liquid crystal displays can be used in projection as well as direct view. The Hughes HighBright^{TM} display technology is based on three a-Si AMLCDs operating in a color projector design; the breadboard system is sunlight readable and has an active display area of 16 x 16 cm (6.25 x 6.25 in.). This technology has been commercialized in a banking application (automatic teller machine). Commercial projectors with p-Si AMLCD devices about 2 x 2 in. compete with DMD for professional presentation markets. A new version, reflective miniature x-Si AMLCD on silicon (LCOS), is due to arrive in projection products in 2001.

4.4 Laser Projectors

Lasers may become the display per se when coupled with a modulator. Laser light is coherent and colors are fully saturated. The coherency translates to a unique feature of direct-modulation laser displays: virtually infinite depth of focus. This means that the image is always in focus, even when displayed on curved or domed screens, as in a custom installation inside a cockpit or simulator. The pure colors provide a wide color spectrum capability. The color range is larger than CRT or LCD based systems. Furthermore, a laser display has better legibility: objects which are fuzzy in a CRT or LCD system are clear in a laser projection of the same image size: luminance and chromaticity contrasts are simultaneously much, much greater. Laser display technological approaches include discrete lasers (both gas, solid state), laser arrays (solid state), and a CRT having semiconductor materials in place of phosphors. The various solid state approaches vary in the pumping mechanism. Projects to make an affordable SXGA solid state laser projector is now underway.[7]

5. Miniature Displays

Research is also underway to establish high resolution miniature displays. The term “miniature display” is a commercial definition for displays whose image must be magnified for viewing. A 12 mm VGA monochrome yellow active matrix electroluminescent (AMEL) display has been developed. The same display has found a direct view application in aircraft annunciator panels as smart, reprogrammable buttons that display diagonal lines smoothly. A miniature 25 mm SXGA monochrome AMEL is completing development and work continues on color. Miniature 12 mm monochrome green CRTs are the baseline technology for the helmet mounted cueing system envisioned in PCCADS. A replacement technology, a miniature 12 mm SXGA monochrome green AMOLED, is being developed as a miniature flat panel display replacement for the miniature CRT. A miniature 25 mm AMLCD at SXGA resolution is being perfected for helicopter helmets. Virtual retinal display (VRD) technology is being developed; color VGA has been demonstrated. Presently, VRD requires too much power and is too bulky for commercialization.

6. System Considerations

Compact supercomputers, known as a multimedia processors, are necessary to drive large area electronic display systems. Also, the functions and screen formats must be determined for this new class of ultrahigh resolution displays.

6.1 Graphics, Video, Information Processors

A supercomputer in a shoebox is required to drive concepts such as depicted in Figures 1 and 2. All information must be integrated in standard formats and graphic generated for the large area of high resolution display surface(s). This processing capability is a narrow-to-wide band processing problem—the inverse of the wide-to-narrow band type of processing problem at radar and electro-optical imaging sensors. The needed improvements in processors may be anticipated based on current, commercially-driven trends.

6.2 Display Format

Once pixels are available they must be filled based on user-in-the-loop studies and crew station integration concept development efforts. Indeed, the creation of the ability to light up more megapixels and the consideration of what to put in them is a synergistic problem to be addressed jointly by the hardware and humanware engineering communities. Transition from monochrome to color pictorial formats were found to provide intuitive presentation and, thereby, a potential reduction in pilot workload. Similarly, a large display is critical to integrate all information in a meaningful, legible way. Future electronic multifunctional displays must deliver both color and large area to support the display format requirements. One day the entire instrument panel of cars and aircraft, and the tops of desks, may consist of one display surface where both pictorial, and alpha-numeric formats will be displayed.

7. Roadmap

The 2.1 megapixel devices needed for high definition (digital) television (HDTV) will come to define the mass market by 2010.[8] The TV standard beyond HDTV may not come until about 2070 with mass production by 2100. The resolution for the 21st century TV standard (HDTV at 2,073,600 pixels) is about 6.75X greater than 20th century TV. Thus, the TV standard for the 22nd century should exceed 15 megapixels.

Rapid growth in resolution has begun. Creation of 20-30 megapixel displays for simulators, sandboxes, cinema, home and office will involve revolutions leading to pixel-surfaces for furniture, walls, and rooms by 2020. Maps for sandboxes require 33 megapixels/m^2. Flexible and printable display technologies, on which research has just begun, will enable wallpaper-thin displays. Many should be able to afford a home “pixel room” comprising 214 megapixels in six sides, by 2100.

Other challenges must be met in order to increase resolution. Specific power density (W/kg) for mobile power sources needs to go up a factor of 10 by 2010 and 100 by 2100. Light generation needs to be made 10-100X more efficient; efficacy in mass production displays should increase from about 4 lm/W in 2000 to 40 lm/W solid state light sources by 2100. Electronics must speed up too: a 30 megapixel device at 48 Hz requires a digital interface of 34.56 Gb/s and storage capacity on the order of 1 petabyte. Image generation processors must be distributed to pixels and segments.

Table III summarizes this roadmap and vision for displays of the future.

Table III. Predicted resolution for display devices. Resolution is expressed in megapixels per device.

Year	Market Classification (end customer sales)		
	Exotic (1-100 units)	Niche (1-10k units)	Consumer (.1-10m+)
2000	5.4 for computer	2, digital cinema	1.9 for PC
2001	1.3 for cockpit	0.3 for cockpit	2.1,HDTV
2010	30 for IMAX	20, web PCTV	4 WCTV
2020	30 for cockpit	20 for simulator	8 WCTV
2100	855 for simulator	214 for home	15,WCTV
~~3000~~	~~Immersive display room: 1.3 gigapixel system~~		

8. Conclusions

The advantages of a large area display system were demonstrated in the Panoramic Cockpit Control and Display System program, a joint research effort of hardware and humanware engineers. The key objective result was a 45% increase in pilot combat effectiveness, which translates to a 31% reduction in the number of aircraft and pilots needed for a given mission. Clearly, large area display systems increase productivity.

Flat panel displays and solid state laser and other projectors present what is, perhaps, the most attractive alternative for achieving panoramic cockpit display technology by 2010. They are light in weight, low in power requirements, and can meet all environmental requirements. Furthermore, FPDs and projectors can scale from sizes used in instrument panels up to synthetic out-the-windows. Total cockpit resolutions of 4-10 megapixels are possible in such near term cockpits. Current cockpits and desktops have just crossed the 1.3 megapixel mark. Thus, a realistic challenge in the near term is an increase of total resolution of 3x to 8x times over the next 10 years. Pixel density needs to increase beyond 200/in. The AMLCD technology has achieved this in the latest IBM announcement in September 2000 of a 9 megapixel, 22-in. display with 200 pixels/in.

By 2020 a variety of improved projector and direct view technologies will be available to build HDD and encapsulated cockpit display systems. Individual displays will be >16 million (e.g. 4096 x 4096) color pixels in 2000 cm^2 (300 in^2) and contoured to fit the curved surfaces of the control panel and inner canopy. Several displays will be tiled to achieve larger display areas.

Flexible and printable displays may lead in the far term to a closable cockpit capsule with pixels on the inside as shown in the immersive cockpit concept. Alternatively projection technology may be miniaturized, or continued evolution of optical tiling of direct-view FPDs may provide the solution. The 210 Mpixel immersive cockpit concept depicted in Figure 2 might become a fielded reality by 2050.

References

1. D. G. Hopper, "*Invited Paper* 21st Century Aerospace Defense Displays," in Society for Information Display (SID) Symposium Technical Digest, Session 29 "Applications: Airborne Displays," 1999, paper 29.1, pp. 414-417 (1999).

2. D. G. Hopper, "Panoramic Cockpit Display," published in *Advanced Aircraft Interfaces: The Machine Side of the Man-Machine Interface*, AGARD CP-521, 1992, pp 9-1 to 9-25. Conference Proceedings of the 63rd Avionics Panel Meeting/Symposium held in Madrid, Spain, 18-22 May 1992. Published by the NATO Advisory Group for Aerospace Research and Development (AGARD) Avionics Panel (AVP).

3. Darrel G. Hopper, "1000 X difference between current displays and capability of human visual system: payoff potential for affordable defense systems," in *Cockpit Displays VII: Displays for Defense Applications*, Darrel G. Hopper, Editor, Proc. SPIE 4022, 378-389 (2000).

4. (a) D. G. Hopper, "Performance specification methodology: introduction and application to displays," in *Cockpit Displays V: Displays for Defense Applications*, Darrel G. Hopper, Editor, Proc. SPIE 3363, pp 33-46 (1998); (b) D. G. Hopper, "Performance specifications: the nearly impossible versus the merely difficult," in *Cockpit Displays VII: Displays for Defense Applications*, Darrel G. Hopper, Editor, Proc. SPIE 4022, paper 15 (2000).

5. *High Definition Systems Program Presentation Summaries"*, DARPA High Definition display technology Information Exchange Conference, 21-24 Mar 1999, 1999. Direct requests to DARPA/ETO, 3701 N. Fairfax Drive, Arlington VA 22203-1714.

6. *Cockpit Displays*, Darrel G. Hopper, Editor,
(a) Proc. SPIE 2219 (1994) 408 pp.;
(b) Proc. SPIE 2462 (1995) 350 pp.;
(c) Proc. SPIE 2734 (1996) 312 pp.;
(d) Proc. SPIE 3057 (1997) 608 pp.;
(e) Proc. SPIE 3363 (1998) 490 pp.;
(f) Proc. SPIE 3690 (1999) 380 pp.;
(g) Proc. SPIE 4022 (2000) 442 pp.

7. K. J. Snell, D. Lee, B. Pati, and P. F. Moulton, "RGB optical parametric oscillator source for compact laser projection displays," *ibid*, 285-289 (1999).

8. "HDTV: You're not going to like this picture—Technical snafus continue to slow its growth," Business Week, October 25, 1999, p. 50.