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1000 X difference
between current displays and capability of human visual system: payoff potential for affordable defense systems [*]

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ABSTRACT

Displays were invented just in the last century. The human visual system evolved over millions of years. The disparity between the natural world "display" and that "sampled" by year 2000 technology is more than a factor of one million. Over 1000X of this disparity between the fidelity of current electronic displays and human visual capacity is in 2D resolution alone. Then there is true 3D, which adds an additional factor of over 1000X. The present paper focuses just on the 2D portion of this grand technology challenge. Should a significant portion of this gap be closed, say just 10X by 2010, display technology can help drive a revolution in military affairs. Warfighter productivity must grow dramatically, and improved display technology systems can create a critical opportunity to increase defense capability while decreasing crew sizes.

Keywords: displays, flat panel displays, human visual system, situational awareness, warfighter productivity, affordability

1. INTRODUCTION

Defense must become more capable yet crew sizes must shrink to achieve the acquisition reform objective: affordability. Warfighter productivity must grow. The search is on for technologies and doctrines that can enable this miracle. Display technology, together with an information dominance doctrine, is poised to contribute. Currently fielded weapon systems in the year 2000 afford the lucky U.S. combatant about 1 million pixel visual display systems. The human visual system (HVS), as discussed in Section 3, is many orders of magnitude beyond the current level of display technology. Increasing the visual bandwidth to individual crew members will enable the necessary increase in warfighter productivity.

2. DISPLAYS: BORN DURING THE LAST CENTURY

Electronic information display is a young science. The television era began in 1927 with a technology demonstration in Germany followed by commercial broadcast initiation in New York in 1939. Requirements from television, sensors and data visualization have driven an explosion in demand for electronic displays over the past 60 years. Resolution in deployed systems has reached about 1 million pixels per display device in civil products. Transition to military crew systems is spotty. The current, operational B-52H cockpit shown in Figure 1 is contrasted to the Rotorcraft Pilot's Associate (RPA) advanced technology demonstration cockpit in Figure 2. The former has just one electronic display, a 9-in. cathode ray tube (CRT), and dozens of electromechanical (EM) instrument displays. The EM instruments may be though of as electromechanical computers with integrated display. The RPA cockpit comprises an array of three 12-in. flat panel displays (FPDs) implemented with active matrix liquid crystal display (AMLCD) technology. Improved electronic computers and flight control systems enable the information presented on the dozens of dedicated EM displays in the B-52H to be relegated to back-up formats. The result is that a single pilot can do the work of two in the RPA design. The same paradigm of using improved display/computer/sensor systems to increase warfighter productivity can be applied to all systems. Lessons-learned on RPA may be applied to advanced combat systems, including RAH-66 Comanche, F-22 Raptor, Joint Strike Fighter (JSF), Army ground Future Combat Systems (FCS), and Navy sea Future Naval Capabilities (FNC).

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Figure 1. B-52H pilot main instrument panel with one electronic display (9-in. monochrome CRT) plus some 60 electromechanical instruments. Cockpit designed in 1950s, built 1960-62. The Air Force plans to operate B-52s until 2046. Note closable screen for nuclear flash and synthetic vision for low level flight (LLLTV or FLIR image displayed on CRT)

Figure 2. Rotorcraft Pilot's Associate (RPA) advanced technology demonstration aircraft cockpit with three 12-in. active matrix liquid crystal displays (AMLCDs) and virtually no electromechanical instruments. Cockpit designed in 1990s, built 1998, flown as non-operational engineering program (one aircraft) to learn how to used advanced electronics to significantly reduce combat crew workload. The total information carrying capacity of this research cockpit is twice that of the F-22A.

3. HUMAN VISUAL SYSTEM: BORN OVER 1,000,000 CENTURIES AGO

Hopper[1] demonstrated that the sampling (pixelation) of a 4π steradian photon flux field passing through a spherical surface may be represented by the equation

$$\text{Npixel}\ (\beta) = 5.3465 \times 10^{11} / \beta^2 \ ,$$

where each pixel subtends a solid angle of $\beta x \beta$, where β is expressed in units of arc seconds. Note that these are pixels (i.e. 2D samples), with voxelation (3-D samples) ignored for purposes of the present discussion. The total number of samples (pixels) needed to represent a spherical photon flux field (4π sr) at various acuities, β, is shown in Table I.

If one picks a particular distance, d, of the display surface from the design eye point, one can compute the lineal pixel density, D_L, from the equation

$$D_L\ (\text{pixels/in.}) = 206{,}270 \ / \ (d\ \beta) \ ,$$

or

$$D_L\ (\text{pixels/in.} \mid d=24\ \text{in.}) = 8{,}594.6 \ / \ \beta$$

Areal pixel density,

$$D_A\ (\text{pixels/100 sq. in} \mid d=24\ \text{in.}) = 100\ D_L^2 \ ,$$

and the pixel pitch, x,

$$x\ (\text{pixel pitch in}\ \mu\text{m} \mid d=24\ \text{in.}) = 25{,}400 \ / \ D_L = 2.96\ \beta \ ,$$

are then readily derived.

Devices with total resolution as high as 5,242,880 pixels have been made.[2] Tiled systems have been built with aggregate resolutions of 28,000,000 pixels.[1] Lineal pixel density for direct-view AMLCDs has recently reached 211 pixels per in. (ppi) with 120 μm color pixels.[3] Miniature displays for projection systems (head-mounted, hand-held, large image) are routinely made with 12 μm pixels. Display devices with pixel pitch as small as 6 μm can be made with present technology.

Table I. Number of pixels in 4π steradians. Pixel densities (lineal and areal) and pixel pitch, at 24 in.

Acuity	**Comment**	**Pixels in 4π sr**	**Pixels / Inch @ 24 in.**	**Pixels / 100 sq.in. @ 24 in.**	**Pixel Pitch (μm) @ 24 in.**
100 arc seconds	Image perceivable	53,465,000	86	738,670	296
84 arc seconds	E-letter, orientation	75,772,000	102	1,048,200	249
50 arc seconds	20/20 vision	213,860,000	172	2,954,700	148
25 arc seconds	2 discs/bars	855,450,000	344	11,819,000	74
14 arc seconds	Detect square	2,727,800,000	614	37,687,000	41
5 arc seconds	Glint, stars *	21,386,000,000	1,720	295,470,000	15
2 arc seconds	Vernier *	133,670,000,000	4,297	1,846,700,000	6
0.5 arc second	Line > 1° *	2,138,600,000,000	17,189	29,547,000,000	1.5

* Real world luminance & chromaticity contrast effects.

Perhaps the most widely know standard for human visual acuity is 20/20. Table II presents a comparison of 20/20 vision to the scene generated by the natural world and perceived by the human visual system. It is clear that 20/20 vision defines but a small fraction of the capability of an ideal display system. The first century of electronic displays addressed little more than 20/20 vision. The next centuries have much potential.

Table II. Comparison of 20/20 vision to natural world scene perceived by human visual system (HVS).

Parameter	**20/20 vision**	**Natural world / HVS**
Ambient Intensity Range	None (fixed @ ~10 lx)	10,000,000x range (10^{-3} to 10^{+5} lx)
Grayscale	1 bit (on/off)	20 bits (all shading nuances included)
Color	No (black / white)	Yes (full, over 32 million colors)
Motion (video)	No (static)	Yes
Content	Letters (ultra simple)	Real world images (ultra complex)
Peripheral Vision	No	Yes
Computer Latency	Zero (static image)	Zero (complex moving image elements)

4. ELECTRONIC DISPLAY TECHNOLOGY CIRCA 2000

Economic viability is used here to categorize display technologies as first tier, second tier, and “wannabe” (want-to-be). First tier technologies support high volume consumer products; that is, they are economically viable in mass markets. Second tier technologies support low volume consumer products; that is, they are economically viable in niche markets. Wannabe technologies support no products, or have not been in the market long enough to establish economic viability.

A mass market is defined herein for displays as involving tens of millions of units per year (installed in products or stand-alone); niche market, tens of thousands per year. One might even define an exotic market involving tens to hundreds of units per year. All military applications fall into the exotic-to-niche range in terms of unit volume.

Specialized versions of consumer mass and niche technologies are used in military products. Military performance specifications are written in any given procurement year to extract more of the technology base into its products than consumer products. However, if no civil product base develops, transition to military products is typically not affordable. Thus, economic viability is a goal of any governmental display research program. The government’s role is that of the earliest, highest risk investor; once the potential has been demonstrated, successful technology advances move on toward market based on years of far larger private investments.

Figure 3 illustrates the status of electronic display technologies in the year 2000 based on these categories. There are just two first tier technologies; cathode ray tube (CRT) and liquid crystal display (LCD). The LCDs include dichroic (dLCD), reflective (RLCD), and active matrix (AMLCD). For both civil and military applications, the CRT still has the largest installed base of any single technology, whereas the AMLCD is the fasting growing technology. The AMLCD technology now dominates notebook computers and is moving into desktop monitors. The AMLCD is the preferred technology in aircraft cockpits (civil and military) and most workstations (civil and military).

There are seven, second tier technologies: digital micromirror devices (DMD); alternating current gas plasma (ACGP); inorganic electroluminescent (EL, TFEL, AMEL); vacuum fluorescent displays (VFD); inorganic light emitting diodes (LED); traditional macro-electromechanical displays (EM); and incandescent light displays (ILD). The DMD technology, which is also called Digital Light Processing (DLP) by its sole producer, Texas Instruments, now commands the professional presentation market against miniature LCD competition, and is poised to take the lead in digital cinema. The DMD is now included in production programs for military workstation displays and is in development to replace CRTs in head-up displays and instrument panels. Plasma technology is succeeding in some television and command room applications. Electroluminescent displays include the traditional, thick film (EL), new low-voltage thin-film (TFEL), and miniature active matrix (AMEL) variants. The EL is often used where monochrome or limited color is sufficient to show symbol or video formats; civil applications include medical instruments and trains; military applications include forward-looking infrared (FLIR) video and head-mounted systems. Vacuum fluorescent displays continue to be used in some automotive applications. The traditional technologies of inorganic LED, EM, and incandescent continue to be used, especially in low-information display applications, where they are cheap, reliable, and fit-for-purpose.

Wannabe technologies abound. Three that have received considerable interest and investment over the past few years are solid state laser projector (SSLP), field emission displays (FED), and organic light emitting diode (OLED) displays. Prototypes exist for these wannabe technologies, but they have yet to be incorporated into any product that has succeeded (i.e. showed staying power) in the market. Solid state laser projector displays include both image-on-screen designs and a head-mounted version known as virtual retinal display (VRD). There are no products using SSLP technology, civil or military. Key technology barriers to SSLP displays include affordable solid state lasers with high efficiency at the correct wavelengths and higher bandwidth modulation devices. The VRD, in particular, faces significant additional challenges, such as the public fear of having a laser beam directed through their pupil rather than onto screen. The FED technology was picked in the mid-1990s by the Defense Advanced Research Project Agency (DARPA) to leap-frog AMLCD technology. The prediction in 1994 was that FED would command 20% of the AMLCD market by the year 2000. The reality now that it is the year 2000: the FED market share is zero. The technology challenges of bringing FEDs to market were significantly underestimated. No products incorporating a FED have showed staying power in the market. New, presently unknown, materials (such as high efficiency low-voltage phosphors) and/or structures (such as anodes that do not cause device failure by continually outgasing when operated at >10 kV for more than a few hours) are needed if FED is ever to become a viable technology. Organic light emitting diode displays and active matrix (AMOLED) displays have evolved very, very rapidly over the past few years and are poised in the year 2000 to become economically viable by 2005. The OLED technology offers the potential for significantly higher power efficiency than available in year 2000 AMLCD technology.

FIRST TIER (economically viable in mass markets)

- **Cathode Ray Tube (CRT)**
- **Liquid Crystal Display (AMLCD, LCD, RLCD)**

SECOND TIER (economically viable in niche markets)

- **Digital Micromirror Device (DMD)**
- **Alternating Current Gas Plasma (ACGP)**
- **Electroluminescent (EL, TFEL, AMEL)**
- **Vacuum Fluorescent Display (VFD)**
- **Inorganic Light Emitting Diodes (LED)**
- **Macro Electromechanical displays (EM)**
- **Incandescent light displays (ILD)**

WANNABE (economic viability yet to be established)

- **Solid State Laser Projector (SSLP, VRD)**
- **Field Emission Display (FED, AMFED)**
- **Organic Light Emitting Diode (OLED, AMOLED)**
- **Et Cetera**

Figure 3. Economic viability status of electronic display technologies. Successful display devices enable the existence and evolution of the television, computer, and information industries.

5. VISION FOR 2010, 2020, 2100, 3000

The resolution of both the natural world (nature's image generation system) and the human vision system exceeds year 2000 technology by many orders of magnitude. A vision for 2010, 2020, 2100, and 3000 is presented in Table III in terms of the metric of resolution per individual display device. Yet higher resolutions will be obtainable, as usual, by tiling. Implicit in this vision is the necessity to simultaneously improve sensors, image generation computers, and support electronics. Also implicit is the need to address the materiel and structure issues needed to increase efficiency (efficacy in lumens per Watt) from about 5 lm/W in year 2000 to, for example, 20 lm/W by 2010, and to 50 lm/W by 2100. Specific power density (W/kg) for mobile power sources needs to go up a factor of 10 by 2010 and 100 by 2100. The manufacturing techniques must improve to enable costs per megapixel to go down by a factor of 10 by 2010 and 100 by 2020. Full true 3D display technology is represented conceptually by the Holodeck of science fiction and is a millennial challenge to be met by the dawn of the 31st century: 1.3 teravoxels are needed.

Table III. Display vision. Metric: resolution (megapixels per display device). *

Year	**Market Classification Category (annual unit sales)**		
	Exotic (1-100)	**Niche (1-10k)**	**Consumer (.1-10m+)**
2000	5.4 for computer	2, digital cinema	1.9 for personal computer (PC)
2001	1.3 for cockpit	0.3 for cockpit	2.1 for high definition television (HDTV)
2010	21 for film pre-production	21 for ads, games	
2010	21 for simulator	2 for cockpit	2 for mobile devices, furniture surfaces
2010	30 for digital IMAX	20, web PCTV	4 for web computer television (WCTV) system
2020	30 for cockpit	20 for simulator	8, WCTV
2070	855, simulator	214 for home	15,WCTV
2100	Vernier display: 2 gigapixels in 100 sq. in. (6 µm pixels)		

* Support and image generation electronics challenges are implicit in the display resolution challenges listed here.
Higher resolutions than shown obtainable by tiling.

The year 2000 technology baseline is the starting point for the vision. Fieldable cockpit display technology in 2000 is represented by the F-22A fighter, RAH-66 Commanche helicopter, and the upgraded C-141/C-130 transport. Each pilot has 650-1300 cm^2 (100-200 in^2) comprising 2 to 6 color multifunction displays (MFD), with one designated as the primary flight instrument and the rest providing other mission or subsystem information as selected. The transport display systems use several displays all the same size to ease the logistics support required and to reduce the number of back-up crews required to support combined C-141/C-130 operations. Commonality remains a challenge area: there are no common display sizes between F-22A and RAH-66 despite years of Congressional demands for common avionics in these two aircraft.

Digital cinema, electronic sandboxes, and integrated web-PC-TV units (WCTV) require display devices with higher resolution. The era of digital cinema began as an exotic market in 1999 with the showing of the movie Starwars Episode I in four theatres from a digital master at 1.3 megapixels per 35mm film frame on two technologies, one based on the Texas Instruments Digital Micromirror Device (DMD) Digital Light Processing technology and another, the Qualcomm/Hughes-JVC CRT/Liquid Crystal Light Valve CineComm Digital Cinema technology.[4] The digital cinema will move from exotic to niche by 2010 as Hollywood plans to see 3,300 digital cinema projectors installed, each with 2 megapixel color resolution.

Digital cinema, as well as high definition digital television (HDTV) will drive volume up and cost down for 2 megapixel display devices and all associated electronics. The 2.1 megapixel devices needed for HDTV will come to define the mass market by 2010.[5] 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 7 times greater than 20th century TV. Thus, the TV standard for the 22nd century should exceed 15 megapixels per display device. Mass markets evolve slower than niche.

The need for yet higher resolution electronic display devices in the exotic markets is exemplified by IMAX.[6] The IMAX movie format provides 30 megapixels per 70-mm frame, or some 15 times the resolution of standard 35-mm film. The image presented can be much larger—the 100 x 80 ft. screen at the Sony IMAX in New York NY is the largest in the western hemisphere. In 3-D IMAX, which was introduced in November 1999 at the Smithsonian in Washington DC, each eye gets a 30 megapixel image. One's instantaneous field of view is almost filled, albeit with just a fraction, about 20%, of 20/20 resolution. And dimness is still an issue: 15 kW quartz lamps are required to create enough light for even a darkened theatre. Turning IMAX digital will require 30 megapixel display devices, or 15X the resolution of HDTV.

Maps for sandboxes require 33 megapixels/m^2 to meet the need for digital devices to replace 1 x 1 m color printed maps.

The 15X goal is realizable by 2010 for exotic and niche markets. Drivers for increased resolution are markets in entertainment, computers, and the internet, which will meld into web-based computer television (WCTV) by 2020.

Rapid growth in resolution has begun. Creation of 20 to 30 megapixel displays for simulators, sandboxes, cinema, data visualization, both at home and office, will drive revolutions in both civil and military affairs, leading to pixel-surfaces for furniture, walls, and rooms by 2010-2020. 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 2070.

The vision for the evolution of displays in defense systems through 2010 is illustrated in Figure 4. Future cockpit design concepts require the creation of a panoramic and immersive display technology base. The opportunity to do so arises from significant continuing investment, by both the commercial and government sectors, to make the impossible possible for an ever-expanding global commercial display industry. In this endeavor the military is the beneficiary of the information age—which it spawned by prior decade investments but which is now driven by the insatiable appetite of civil markets for more and better visual communication and entertainment devices. Our strategy is to pursue multiple technological approaches: revolutionary new display technologies, groupings (arrays or seamless tiling) of flat panel displays, and projectors. We are funding, together with the Defense Advanced Research Projects Agency (DARPA) several different methods within each of these approaches.[7] The engineering design opportunity will be realized in fielded weapon systems only if the operational community accepts the vision. We expect that it will because of the environment in which future warfighters and professionals are growing up: panoramic video games and learning systems, and immersive IMAX movie theaters. Pilots, sailors, soldiers, and astronauts not only will accept panoramic and immersive displays in the "cockpit", they will expect and demand them.

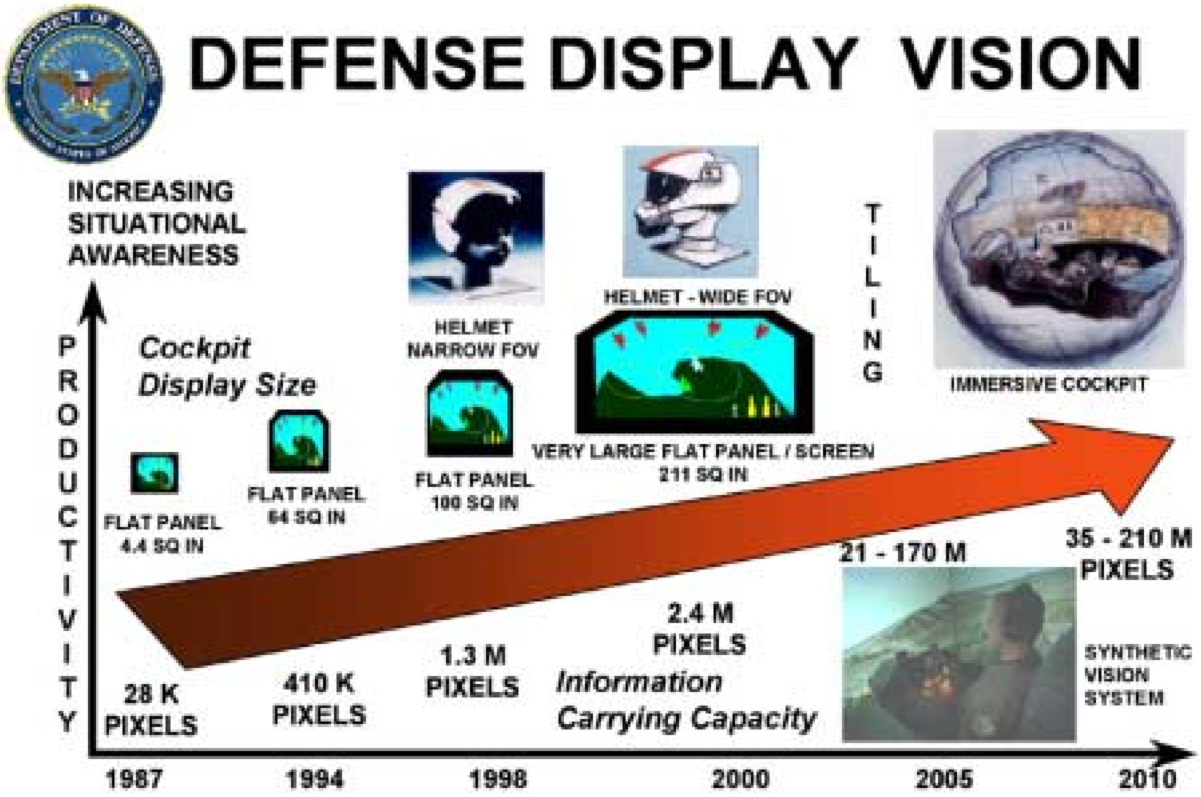

Figure 4. Defense display vision.

This vision enables the cockpit concept for 2000, illustrated in Figure 4, comprising a 2000 cm^2 (300 in^2) panoramic direct view head-down display (HDD) system coupled with a simple helmet display for off-boresight cueing of smart munitions. The head-up display (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.

By 2010 the cockpit canopy may be turned opaque to all optical wavelengths for mission segments flown within the threat envelopes from air, ground, or space anti-personnel laser weapons 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 and on/off-board sensor suites.

6. DEFENSE PAYOFF POTENTIAL

Affordability is defense policy. More military capability for less money will require increases in warfighter productivity. Display technology is poised to contribute. Improvements in sensors, computer image generators, and displays are all needed to enable design of upgrades and new systems so operators can reduce metrics like \$/target or \$/ton-mile. However, display technology is the tall technology pole in the year 2000.

Sensor systems already require far more resolution and greyscale than currently fields display technology can support. Larger, higher resolution displays will enable more complex threat environments to be displayed so that pilots and combat crewmembers can establish situational awareness over ever more dense threat environments with real-time-in-cockpit information presently reserved for intelligence analysts and unavailable to tactical crews until after it is too late.

Computer image generation capability is far ahead of display technology too. Simulator displays are so low in resolution that trainees are legally blind. Training and mission rehearsal can only be taken so far in simulators because the display systems are so poor in resolution and luminance. The most conservative view (see Table I) is that a fully immersive, 4π sr, synthetic vision system (SVS) would require the 214 megapixels to provide its occupant even just 20/20 resolution (see Table II for the limitations of 20/20 vision). The year 2000 state-of-the-art for an SVS is represented by tactical aircraft simulators, for which 15.36 megapixels are generated by tiling eight 1600x1200 (1,920,000 pixel) projectors behind eight screens tessellating a sphere surrounding a trainee seated in a cockpit.[8] For 20/20 a cockpit SVS must provide some 161 megapixels in the solid angle (80% of 4π sr) out of a fighter aircraft bubble canopy. The SVS 20/20 challenge is to increase resolution by the ratio of 171/15.36, or 11.1X. Thus, display devices of resolution 11.1 x 1.92 megapixels, or 21.4 megapixels, are required. A challenge of 10 to 15X increase in display device resolution is a reasonable goal for the display community to achieve by the year 2010. Yet higher SVS resolutions are wanted, leaving much to be done beyond 2010.

Future battlefield threats will require the creation and fielding of panoramic and immersive “cockpits” for air, land, sea, and space systems. Tactical aircraft cockpits exemplify the need. The direct view now acquired by the pilot's unaided eyes looking out of current cockpits might be denied even during a clear weather day by directed energy threats. Rules of engagement, however, require human-in-the-loop to the last moment possible before munitions release and during fly-out to ground targets to minimize collateral damage and civilian casualties. In addition, combat pilots suffer from information overload resulting in loss of situational awareness at times when it is most important: in combat. Beyond visual range objects are difficult to envision and fit into a total picture due to small size (<50 sq.in.) of fielded cockpit displays. Also, sensor advancements provide ever higher resolution targeting imagery real time in the cockpit. These threats, together with night, in-weather, low-level flight conditions are giving rise to the need for large head-down panoramic displays in 21st century cockpits and make the case for exploration of immersive displays.

As agile frequency lasers become more ubiquitous, military—and even civilian—pilots might have to fly some flight segments without looking out of the cockpit. The canopy would be closed by curtains or by an electrically controlled opaquing layer—only during these times. Then a synthetically generated view of the real world would be created. The control and display system might logically evolve as an extension of present day night/in-weather instrumented flight systems. A more extensive in-cockpit display suite may become necessary to survival and mission success. Such a system might include a 4000 cm^2 (600 in^2) head-down color multi-function display that would be viewable in sunlight or starlight, plus a helmet-mounted cueing system. The opaqued cockpit might include a closable canopy display to provide simulated vision over the full field of view, a view denied episodically during some missions by external conditions. Ideally the individual display units comprising the closable display system would be physically redundant yet appear seamless.

Before going on it is useful to note that protecting pilots from bright light and providing them with synthetic vision in lieu of a view out the cockpit window is not a new problem. The B-52 cockpit shown in Figure 1 had window shades for nuclear flash protection and presently has a 9-inch display to show FLIR/LLLTV to the pilots while flying at night at very low altitude. However, the new thrust to create a flexible display technology base, just begun by DARPA, might one day (about 2010) enable these closable screens, initially just for protection against nuclear flash or lasers, to become additional display surfaces.

A program of studies conducted in the early 1990s demonstrated an effective way to increase fighter pilot productivity. The approach in this program, entitled "Panoramic Cockpit Control and Display System (PCCADS)," is to provide the pilot with large area displays and a helmet-mounted off-axis target-acquisition weapon-targeting system.[9] There were two projects, one focused near term, one far. 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 comprising six flat panel AMLCDs with an aggregate resolution of 1.35 megapixels at 5-bit greyscale in 1290 cm^2 (201in^2) plus helmet cueing. Beyond the PCCADS 2000 cockpit was PCCADS: a 2000 cm^2 (300 in^2) seamless head down display system implemented in a physically redundant fashion. This research demonstrated pilot productivity payoff from bigger, better displays.

A super-panoramic cockpit (SPC) with features beyond PCCADS is illustrated in Figure 5. The SPC concept is PCCADS plus (a) left and right curved instrument panel "wing" displays, (b) flip-up FPDs, and (c) closable canopy display. A closable curtain inside of the canopy in the near term gives way to a flexible canopy display in the far term. Stowable FPDs or projection screens are deployable either side of the HUD.

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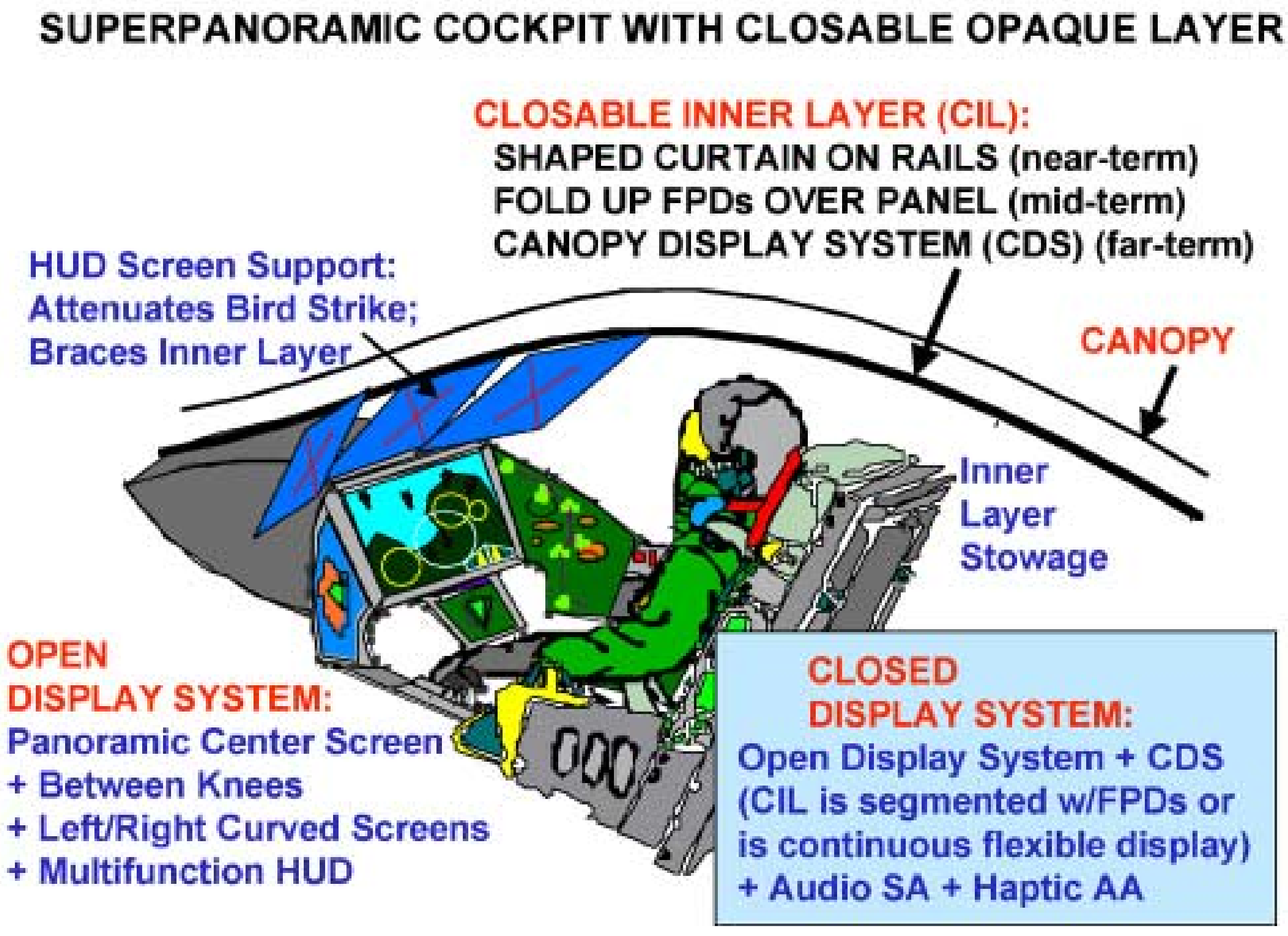

Figure 5. Concept for 2010: ***Super Panoramic Cockpit Plus***

The 2020 vision is an encapsulated cockpit as illustrated in Figure 6. Concepts beyond 2000 will switch from the outside-looking-in (OLI) to the inside-looking-out (ILO) approach. One develops the sense that one is *inside* an artificially generated scene, or world, when the IFOV exceeds about 100° x 50°. The pilot may have no windows and their cabin may be a self-contained spheroid embedded within the aircraft or, possibly, elsewhere. This display system might be that of a present-day trainer/simulator–only far, far better in luminance range, color and 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. The capsule is a node in the battle network.

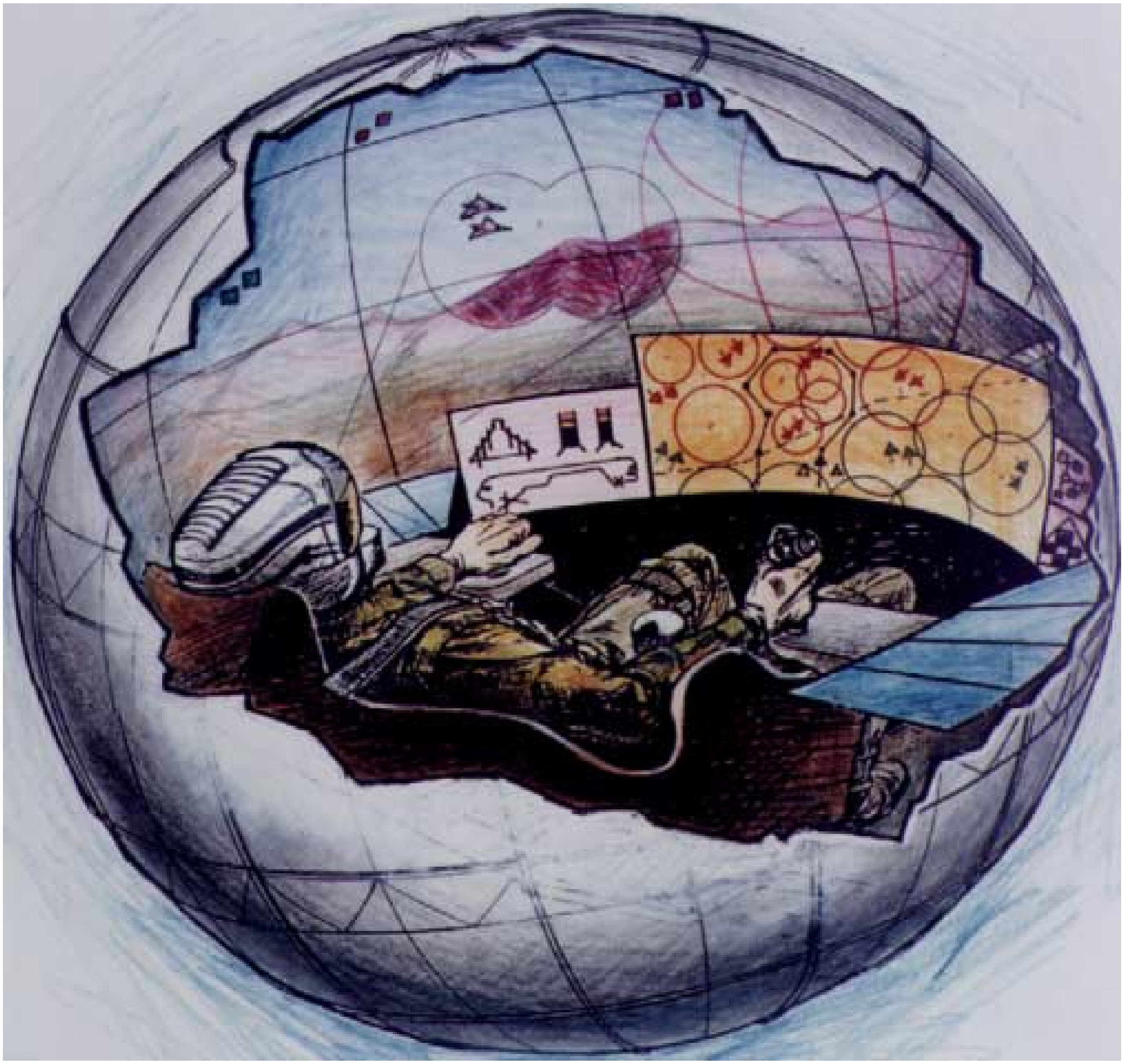

Figure 6. Concept for 2020: ***Immersive Cockpit.***
Encapsulated crewspace realized via combination
of direct-view, projection and head-mounted displays.

The grand challenge for display technology is to close the fantastic 10^6 gap between devices and the human visual system. Predicting the pace of technology is difficult. Wilber Wright[10] predicted in 1909 that "No airplane will ever fly from New York to Paris" because the motor would not take the stress and the airplane "will always be a special messenger, never a load carrier". Within 20 years Wright's predictions were proven far, far too conservative. Yet, science fiction does not readily become science fact for mass markets like TV. Both of these concerns have been considered in establishing a vision of how fast the 1000X difference between current displays can be closed to enable affordable defense systems. A goal of 10X device resolution increase by 2010 will enable a revolution in military affairs as it will drive warfighter productivity.

7. REFERENCES

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