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A Vision of Displays of the Future *

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ABSTRACT

Electronic display is a young technology. Only for a few decades have such displays been in common use. Now many applications provide 0.5-1 million picture element (megapixel) visual interfaces in two-dimensions with acceptable grayscale, frame rate, and so forth. However, the human visual system is capable of more than 1,000 megapixels (1 gigapixel) in three-dimensions. Thus, much opportunity remains. A vision of how fast we may close this gap during the next decade, century, and millennium is presented.

DISPLAYS: BORN IN THE 20th CENTURY

The era of electronic display began some 60 years ago when cathode ray tube (CRT) technology matured enough to create applications such as television and radar. Luminance was an issue: dim rooms or shrouds were necessary to see the image. Luminance is still an issue for CRTs. Despite decades of trying, humans never ever made a CRT bright enough to provide full sunlight readability (SR) for fighter cockpits and banking machines. Resolution for video CRTs quickly moved up to current mass market standards such as NTSC for TV, and the approximate computer monitor equivalent of VGA (307,200 pixels). Resolutions for CRTs in dim ambient illumination applications grew to SXGA (1,310,720 pixels) in 19 inch diagonal size for niche markets. A 2,000 x 2000 (4,000,000 pixels) resolution in 20x20 inch size was briefly available for exotic specialty markets. These niche and exotic high resolution, large direct view CRTs have now mostly ceased production with exception of some for high definition television (HDTV) 1920 x 1080 (2,073,600 pixels). Exotic avionics CRTs from miniature 0.5 inch diameter up to about 6x6 inch were developed that were bright enough to be viewable in many, but not all, SR situations, and then only if written with very low screen fill factors in stroke mode. At night CRT imagery “floated.” As the century ends CRTs are about to be replaced by flat panel display (FPD) technology.

By 2020 CRTs will have the same place in electronic display as horses now have in transportation. The car replaced the horse for flexible personnel transportation over the period 1900-1920. The FPD is replacing the CRT over the period 1990-2010. The dominant FPD technology is the active matrix liquid crystal display (AMLCD), with others such as digital micro-mirror device (DMD), new electro-luminescent (EL), and light emitting diode (LED) also economically viable. The FPDs have enabled new applications like notebook computers, personnel digital assistants, and sunlight readable glass cockpits over the last ten years or so.

The epochal shift from CRT to FPD is evident in the installed base of electronic displays. Hopper and Desjardins[1] analyzed displays in systems throughout the U.S. Department of Defense. Figure 1 shows that defense displays are *already* dominated by FPDs (AMLCD, LCD, LED, EL, and plasma technologies).

Display technology is just begun. As human knowledge grows, far higher resolutions will be built.

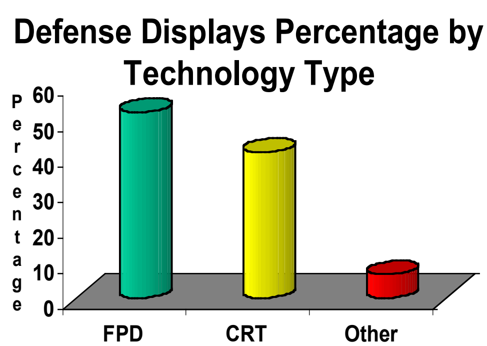

Figure 1. FPDs are now more common than CRTs among electronic displays installed in defense systems.

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HUMAN VISUAL SYSTEM

The capacity of the human visual system is estimated here on the basis of the number or resolvable pixels needed in the surface of a sphere surrounding a design eye point. One might imagine a person suspended in space but able to look at will in any direction. Full motion video (no computer latency) and full grayscale are assumed in the present discussion--just as in nature.

The solid angle at the design eyepoint is 4π steradians. A pixel corresponds to a solid angle of $\alpha \times \alpha$, where α is expressed in radians. Thus, the number of pixels needed for a two-dimensional representation of the resolution available in nature with discrete samples is

$$\text{Npixel} = 4\pi / \alpha^2$$

Equivalently, one can compute the number of pixels needed on the surface a sphere of arbitrary radius r. The area of the sphere is $4\pi r^2$. The distance d subtended on the surface of the sphere by an angle α, is

$$d = r \sin(\alpha) \approx \alpha r$$

At the surface of the sphere a resolvable pixel has area

$$\text{Apixel} = d^2 = (\alpha r)^2$$

The number of pixels of size d x d needed on the surface of the sphere to provide this resolution is

$$\text{Npixel} = \text{Asphere} / \text{Apixel} = 4\pi / \alpha^2$$

The conversion factor for arc seconds to radians is

$$1 \text{ arc second} = (\pi / 648{,}000) \text{ radian}$$

Thus,

$$\alpha = \beta\,(\pi / 648{,}000),$$

were β is expressed in arc seconds, so that

$$\text{Npixel}(\beta) = 4\pi / (\beta\pi / 648{,}000)^2$$

$$= (1.679616 \times 10^{12} / \pi) / \beta^2$$

$$= 5.3465 \times 10^{11} / \beta^2$$

For the widely used standard for human visual acuity, 20/20, defined here as the ability to resolve elements as small as 50 arc seconds, the total number of resolvable pixels in 4π steradians is

$$\text{Npixel}(\beta{=}50) = 2.1386 \times 10^8$$

However, 20/20 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) and luminance contrast is often sufficient to resolve objects smaller than 50 arc seconds. Also, 20/20 is defined for black/white luminance contrast and ignores color, 3D, and motion as image resolving features of human vision.

Human visual acuity is much finer than 20/20 implies. Stars subtend far less than 50 arc seconds, perhaps as small as 5 arc seconds in some cases—yet people see stars. Similarly, glint from a highly reflective surface is readily visible, but often subtends 20-25 arc seconds or less. Thus, 4π sr 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 4π sr are provided in Tables I and II.

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) actually exists in the real world scenes over 4π sr. Also, the high rate of eye scan, combined with the sensitivity of peripheral vision to motion, requires full image be present continuously at full visual acuity over 4π sr, ideally, just as in Nature.

Table I. Number of resolvable pixels in 4π 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 4π 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

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* Holodeck of Starship Enterprise ≈ 1 trillion voxels.

DISPLAY METRIC: RESOLUTION

Resolution is used in this paper as metric for the pace of past progress and to develop a vision for future developments. Other factors, such as display design, manufacturability, and affordability will be gradually overcome in order to raise resolution. Full grayscale, color, angle, video performance are assumed herein except as noted otherwise. For reference, some milestones for individual electronic display devices over the past 60 years are presented in Table III. Systems applications involving tiling over the past 104 years are presented in Table IV to illustrate pent up demand for far more resolution—to close somewhat the gap with ideal resolutions (see Tables I and II).

Projections for the future are summarized below in Table V for 2D displays and in Table VI for 3D.

Table III. Resolution trends for display devices. * Resolution is expressed in millions of pixels.

Year	Market Classification (end customer sales)		
	Exotic (1-100 units)	Niche (1-10k units)	Consumer (.1-10m+)
1939	0.3 for b/w TV	1 for b/w movie	0.01 signs
1949	0.3 TV	1.3 for movie	0.3b/wTV
1959	0.3 for cockpit	2.0 for movie	0.3 for TV
1979	1.3 for computer	0.3 for cockpit	0.3 for TV
1989	4.0 for ATC **	1.3, computer	0.3 for PC
1998	2.1 for HDTV	1.9, computer	0.8 for PC
1999	60 for 3D IMAX	2.1 for HDTV	1.3 for PC

* Dates are approximate. **ATC: air traffic control

Table IV. Aggregate resolution for tiled systems.*

Year	Exotic (1-100 units); no mass markets exist.
1895	U.S. World's Fair, some 12 arc lamp b/w slide projectors mounted on a tall platform at center of large circle of big screens; visitors walked into huge area between platform and circle of screens to enjoy a 360^o immersive display.
1955	Cinerama (equivalent to 4-6 megapixels) 3 synchronized color movie projectors with a tiled screen arranged in 100^o arc
1990	Amusement parks 360^o immersive exhibits using electro-optics projection technologies
1996	Simulator, Mesa AZ, St Louis MO, 8 UXGA 16 megapixels/frame (trainee is legally blind)
1997	Newseum, Arlington VA, 90 TV 28 megapixels, different channel each screen
1998	Advertisement set design, 100 TVs or PCs 31 megapixels per wall or per igloo
1999	Discovery Store, Sony Metreon, SF, 70 TV 22 megapixels, up to 12 screens per channel
1999	Stock Exchange, an immersive display design: FPDs everywhere,above head, eye level, down

* Dates are approximate.

DECADE CHALLENGES FOR 2010-2020

The capacity of the human visual system, summarized in Table I, shows a need for displays to grow in resolution by a factor of 200X to 1300X from the current mass market standard of about 1 megapixel. For example, the most conservative view is that a fully immersive, 4π sr, synthetic vision system (SVS) would require the 214 megapixels to provide its occupant(s) 20/20 resolution. The 1999 state of the art for SVS's is represented by tactical aircraft simulators: 15.36 megapixels generated by tiling eight 1600x1200 (1,920,000 pixel) projectors behind eight odd-shaped screens surrounding a trainee seated in a cockpit. Just a fraction, 50-80%, of each display device image hits the screen (odd-shaped screens mapped to rectangular display devices); the effective SVS is actually 12.3 megapixels, or less.[2] Thus, a cockpit SVS needs 161 megapixels to cover 75% of 4π sr. The SVS challenge is to increase resolution by the ratio 161/12.3, or 13X. Thus, display devices of resolution 13x1.9 megapixels, or 25 megapixels, are required. A challenge of 13X for display device resolution is a reasonable goal for the display community to achieve by the year 2010.

Digital cinema, electronic sandboxes, and integrated web-PC-TV units (WCTV) also 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.[3] Meanwhile, film cinema has moved the bar up with the introduction of IMAX and, in 1999, 3D IMAX.

The highest resolution used in any current application is 3-D IMAX.[4] IMAX film provides 20-30 megapixels per 70-mm frame, or 10-15X that of 35-mm, so the screen can be much larger. The 3-D IMAX is just being introduced in November 1999: each eye gets a 20-30 megapixel image from e.g. the 100 x 80 foot screen at the Sony IMAX theatre in New York (largest in the western hemisphere). One's instantaneous field of view is almost filled. Dimness is still an issue: 15 kilowatt quartz lamps are required to create enough light for even a darkened theatre. Turning IMAX digital will require 30 megapixel display devices.

The 13X goal for 2010 pertains to exotic and niche markets, defined here as 1-100 and 1,000-10,000 units sold per year, respectively. Drivers for increased resolution are mass markets in entertainment, computers, and the internet, which will meld into web-based computer television (WCTV) by 2020.

CENTURY CHALLENGES FOR 2100

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 6.75X greater than 20th century TV. Thus, the TV standard for the 22nd century should exceed 15 megapixels per display device.

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 1999 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 V. 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		

Table VI. Resolution for true 3D.*
Units: megavoxels per display system

Year	Market Classification (end customer sales)		
	Exotic (1-100 units)	Niche (1-10k units)	Consumer (.1-10m+)
2020	1,000	0.1	0.01
2100	214,000	21,000	1,000
3000	Holodeck: 1.3 teravoxel, tiled design **		

* Autostereoscopic with multiple views per eye.
** Computer architecture includes chips in brain to signal haptic feedback and to collect control signals.

NANOHOLOGRAPHY and HOLODECK 3000

True 3D. Three-dimensional displays will develop more slowly than 2D via three approaches: holographic, volumetric (direct write), segmentation (lateral array of 2D views). Materials and device fabrication challenges appear impossible—truly a long term problem. High fidelity true 3D monitors should appear during the 21st century. Nanoelectronics, for example, might enable fabrication of 25 nm hologram pixels (hpixel) across 100 sq. in. of a 16 in. wafer; the resulting sampled hologram (10^{14} hpixels) might correspond to a true 3-D resolution of 1.5 gigavoxel in a 30^0 field of view by 2100.

Holodeck. 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.

SUMMARY

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[6] 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 for displays of the future.

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