Display Characteristics and the Impact on Usability for Stereo

John W. Roberts and Oliver T. Slattery

National Institute of Standards and Technology[1], MS 8951, Gaithersburg, MD 20899

ABSTRACT

Over the past decade, the number of electronic display technologies available to consumers has risen dramatically, and the capabilities of existing technologies have expanded. This proliferation of choices provides new opportunities for visual stereo presentation, but also new challenges. The methods of implementing stereo on an electronic display, optimized for the original capabilities of the original displays, may no longer be the best choices. Features such as response time, frame rate, aspect ratio, sync timing, pixel registration, and temporal modulation of grayscale (brightness) and color can strongly influence the process of selecting an optimum presentation format for a given display technology. Display performance issues such as brightness, contrast, flicker, image distortion, defective pixels, and mura are more critical in 3D imagery than in 2D. Susceptibility to burn-in limits the implementation choices for a display that is to be used for both 3D and 2D applications. Resolution and frame rate establish the overall capability for representing depth, and also establish the performance requirements for the engine providing the 3D material.

This paper surveys the capabilities and characteristics of traditional displays such as CRT and LCD panel, and a broad assortment of newer display technologies, including color plasma, field emission, micromirror and other reflective systems, and the general classes of microdisplays. Relevance of display characteristics to various stereo presentation formats is discussed, with description of laboratory experimentation to provide hard numbers. Recommendations are made regarding the stereo formats to be used with various display technologies, and the display technologies to be used with various stereo formats.

1. INTRODUCTION

While the imaging capability of a human eye is essentially two-dimensional in nature, the perception of depth and the mental reconstruction of a three-dimensional universe are major components of human visual capability. Similarly, presentation of stereo has been a recognized component of photography for almost as long as photography has been in existence. One of the key accomplishments of the second half of the 1900s was the explosive growth in information processing and display capabilities. It is hardly surprising, therefore, that much attention has been paid to the use of displays for presentation of stereo. Despite extensive efforts along these lines, stereo remains only a minor component of the total market and usage of displays – in large part this is because of display characteristics that limit their usefulness in presenting stereo.

Characterization of displays for stereo is a “moving target”, because new display technologies continue to appear, and performance capabilities of many existing display technologies continue to improve. But such characterization is important, because it permits identification of the bottlenecks to stereo display performance, serves a guide for optimizing stereo performance of existing displays, and shows a path for continued improvement in stereo displays and continued growth of the stereo display market.

The emphasis of this paper is on the use of display technologies as a tool for stereo presentation. It begins with a brief review of the principal human visual requirements for stereo, then a general overview of the display methods that are used to present stereo. This is followed by a description of display characteristics that limit usefulness for stereo, and a listing of display technologies and their respective issues for stereo presentation. A set of recommendations is presented, based on known display characteristics, on the matching of display to presentation technique to subject for optimum stereo results with existing systems. Next is a description of methods being used to detect and identify new or previously unknown display characteristics, and what impact these new characteristics can have on stereo presentation. Finally, the paper speculates on an optimization path for future displays for stereo application and a pathway to increased use of displays for stereo.

It is possible to think about stereo displays from a number of different points of view. The new point of view described in this paper of display performance in stereo display systems provides useful insights, that hopefully will promote improved stereo display technology and application both now and in the future.

[1] Certain commercial products are identified here in order to document our experiments. Identification of such products does not imply endorsement by NIST.

2. HUMAN VISUAL REQUIREMENTS FOR STEREO

The human visual system combines many elements for the overall perception of depth . These can include 2-D image cues such as perspective, objects hiding behind other objects, apparent size of objects of known size, relative sizes of objects, distance-related lighting effects, and so on. It is not always necessary for all of these visual cues to be provided in order for the viewer to perceive depth, but omission of cues can affect overall quality of depth perception, and limit the range of what can effectively be portrayed. Similarly, in the specific area of stereo perception, there are a considerable number of conditions that must be met for "ideal" stereo viewing under all conditions. The failure to meet one or more of these conditions can lead to interference with one or more of the cues that humans combine for stereo perception. Unfortunately, no existing display (or photographic) system is able to correctly provide *all* of the depth cues. Fortunately, the human visual system is often able to correctly perceive stereo in the presence of incorrect or conflicting visual cues – roughly speaking, this is done by combining and weighting the importance of various cues, choosing which to trust and which to discount in building up a mental model of a 3-D view. It is this capability that makes use of stereo displays (and photographic systems) possible, despite their imperfections. Given the fact that stereo displays can be used despite their imperfections, the main effects of these imperfections are progressive degradation of the stereo experience as the shortcomings become more significant, leading at some degree of imperfection to a breakdown of meaningful stereo perception, and a disproportionate degradation of stereo perception for certain types of scenes and stereo applications that rely most heavily on the display characteristics that are flawed. The end result of these effects is that any stereo display, because it has imperfections in its recreation of the 3-D experience, will be useful for a certain range of stereo applications, marginally useful at the extremes of this range, and not useful outside of this range. The exact range of useful applications for a given stereo display depends both on the characteristics of the display and on the human user who is viewing the display – different people will have different thresholds of tolerance for display imperfections.

An absolute measure of the usefulness of a given stereo display for a given application is therefore a matter of probabilities, depending on the population distribution of human perceptual characteristics, and complicated by the fact that through training, many humans can learn to alter their perceptual characteristics. Such a rigorous mathematical treatment of human perception is beyond the scope of this paper – particularly since the emphasis of the paper is on display characteristics. Instead, a fairly simple set of generalizations will be used, describing the visual requirements of *most* people for a worthwhile and valid stereo viewing experience.

There are also a number of safety concerns that have been raised regarding the prolonged use of stereo displays, particularly head mounted and virtual reality systems. It is incumbent on manufacturers of stereo display systems to be aware of and address these concerns as needed – such issues are also beyond the scope of this paper.

In general, and in terms of display performance characteristics, the following are significant human visual requirements for viewing of stereo images:

- Different views of the scene must be provided to the left and right eyes. The two views must have proper left-right positioning to allow realistic convergence of the eyes when viewing.
- The stereo image displayed must feature an absence of retinal rivalry (non-stereo disparities between the left and right views).
- The left and right views must feature correct geometry – for example, keystoning effects should be neither greater than nor less than those inherent in the human visual system. If the left and right views are limited in angular size to less than the full field of view of a human eye, then the shapes of the boundaries should be consistent (the "stereo window").
- The display should provide correlation of convergence of the eyes and accommodation (focus). (No current two-image stereo display systems have fully implemented this capability.)
- The left and right views should be time synchronized, both the whole views and the components of the views, to within the timing required for human stereo perception.
- To the greatest extent possible, the view should reproduce human visual capabilities, for example in resolution, field of view, color, contrast, update speed, and dynamic range.

Again, note that no stereo display system fully meets all of these requirements. Also note that "resolution" has different meanings in different contexts, and can affect stereo perception in different ways; examples of different types are resolution relating to the luminance of an image, color resolution, vernier acuity, and stereo acuity.

3. GENERAL OVERVIEW OF DISPLAY METHODS FOR STEREO

Throughout the history of displays, an enormous number of specific techniques have been introduced for the representation of 3-D displays. Those that permit true stereo viewing can be divided into three main categories: 1) two-view displays, 2) volumetric displays, and 3) holographic displays. Two-view displays are by far the most common; common two-view display types are autostereo, frame/field sequential, two separate views on one display, two separate displays, color-based separation, and Pulfrich Effect stereo. The general principles, general operational characteristics, and general display capabilities of each approach will be described below.

- **Two-view displays (generic):** Two-view displays provide the user with the two views needed for stereo viewing from a single point of view. They are closest in concept to the traditional methods of stereo photography. They are also able to do so at a given image quality while requiring the transport and display of no more than twice the information of a 2-D display of comparable image quality. As a group, they suffer two significant disadvantages compared to other 3-D displays: they can only present one point of view at a time, and if the user gets too far out of alignment with the preferred viewing angle/position, geometric distortions appear that interfere with proper stereo viewing. Each of the major types of two-view displays has its own strong points and weak points from the viewpoint of display presentation:
  - **Autostereo displays:** Two-view autostereo displays are designed for direct viewing of the same display area with both eyes, with a left view presented to the left eye and a right view presented to the right eye, thus avoiding the need for the use of any specialized headgear. This is an advantage for many users and applications. The principle of such displays is comparable to that of lenticular or barrier-strip stereo photographs – either vertical bars or vertical lenses are built into or mounted on the display, permitting or blocking certain parts of the underlying display from view at certain horizontal angles from the display, so that when correctly placed, the left eye sees only those parts of the image that were intended for left eye view, and the right eye sees those intended for right eye view. While avoiding the use of optical headgear, displays of this type face certain challenges in their engineering and use: 1) Typically resolution is traded off for stereo capability, so these displays have only half the spatial resolution of comparable non-stereo displays. 2) The user must be positioned in any of one or more "sweet spots" (positions/angles where the geometry works to present the correct views to each eye) in order for the stereo to work properly – outside of the sweet spots, the image may be blurred, the stereo may be lost, or the view may be pseudoscopic (left and right views reversed). 3) The design geometry must take into account both interpupillary distance (which varies considerably from person to person), and distance from the screen. 4) Designs must trade off directionality and brightness – at best an autostereo display will appear only half as bright as a comparable conventional display. 5) For a wide angle of view (e.g. a large display viewed close up), the angle of view to each eye is considerably different from different parts of the screen. This complicates design of wide-angle autostereo displays. 6) Because of the precise alignment required, the optical elements for a two-view autostereo display must generally be permamently mounted to the display. Thus if the user wants to use the same display for 2-D viewing, it is not practical to remove the optical elements, and many of the disadvantages for stereo still apply (at least to some extent) for 2-D use.
  - **Frame/field sequential displays:** Frame or field sequential displays show left and right views on a conventional 2-D display, but alternating in time. The user employs some method (typically shutter glasses, though systems have been built using circularly polarized glasses and a switchable polarizer on the display) to separate out the views to each eye. A major advantage of this approach is the ability to use conventional 2-D display technology. For example, commercial systems have been produced to allow stereo viewing with a conventional home television receiver and VCR, plus control equipment for switching the shutter glasses in sync with a signal embedded in the video source. The most successful systems for viewing stereo on a computer are also based on this approach. The advantages or disadvantages depend on the particular method used. Field sequential systems trade off vertical resolution for stereo capability (the alternate lines in the interlaced image are used for the left and right views), while frame sequential systems allow full spatial resolution, but trade off temporal resolution – the image update to each eye is only half that of the same system used for 2-D display. Lower image update rate can lead to the perception of flicker, and to the loss of synchronization of left and right images in fast-moving video. Time synchronization issues can be addressed only by choice of content for fixed formats such as NTSC, PAL, and broadcast HDTV, but can be addressed in high-end computer display systems by choosing a high frame refresh rate, thus extending the range of what can be displayed to produce usable results.
  - **Two views on one display:** A number of stereo display methods put left and right views on one display. Specific techniques include interlaced images (described above), side by side, top/bottom (one image in the top half of the display area, and one at the bottom of the display), and systems based on cross-polarization of alternating areas of the display. In all of these implementations, an optical device (mirrors, lenses, polarizers, etc.) is used to separate out

the left and right views as seen by the user, and place them in the correct spatial orientation. Displays of this type can be made using standard 2-D displays, and can generally be used in full-frame 2-D mode, so the resolution tradeoff for stereo capability only effects use for 3-D. Side by side and top/bottom displays have two additional issues: 1) For efficient use of the pixels available on the display, the aspect ratio of the left and right images is generally not one of the usual choices such as 4:3 or 16:9. The implementation choices are to perform a geometric transformation of the image to correct it to a preferred aspect ratio, to use non-standard aspect ratios, or to use left and right images with the preferred aspect ratio, possibly allowing much of the resolution capability of the display to remain unused. 2) Most display technologies update the display in a scanning fashion, a pixel at a time or a line at a time, the most common method being fast horizontal scan left to right (or a horizontal line at a time), as part of a slower vertical update, top to bottom. The relative positioning of the two images can therefore make a difference when certain fast-moving, distinct video images are shown, since it affects the synchronization of the left and right images that must be combined by the brain for perception of stereo. In most display systems, side by side images have closer time correlation of homologous points than top/bottom images.

- **Two separate displays:** Two separate displays may be used for stereo by mounting them in a headset, one display for each eye, or by some other means of optical combination, e.g. two projection displays with polarizers, directed at a screen for view using polarized glasses. Such systems are at least twice the cost of a 2-D display of comparable type, but offer the advantages of full resolution and full brightness for stereo images. Design issues are precision alignment of the two displays (and adaptation to user interocular, for head-mounted displays), and the storage, transmission, and synchronization of the two video streams.
- **Color-based separation:** Anaglyph stereo is the most common color-based separation technique. The left and right views are encoded in two different colors, and viewed through colored filters that separate the view to each eye. Anaglyph can be used to display stereo on a conventional 2-D display, but if the spectra of the color elements in the display are not well matched to the filters in the viewing device, or if there is significant overlap in the spectra used for left and right views, the display will exhibit poor extinction, and there will be resultant ghosting of the images. Anaglyph affects the color fidelity of the stereo image, and its effectiveness depends partly on the color composition of the subject being displayed. Another color-based separation technique uses diffractive optics in a viewing device to shift the apparent angle of view of objects in the field of view, by an amount that corresponds to the wavelength (and therefore color) of the object. By reversing the direction of shift to the left and right eyes, and by careful choice of color composition of the scene displayed, a limited amount of apparent depth can be generated. This technique is not useful for general purpose stereo, but can be applied to special cases, for example depiction of multilevel diagrams. In general, the development of color-based separation is more mature in print media than in displays.
- **Pulfrich Effect stereo:** Pulfrich Effect stereo presents a scene from a laterally tracking point of view, with the view to one eye darkened, thus resulting in an apparent time delay in the brain's interpretation of the view from that eye. If all the parameters are set correctly, this provides what is effectively a time-based stereo separation for the views to the left and right eyes. Pulfrich stereo can be used with a conventional 2-D display, and can provide highly effective stereo to many users. It requires careful staging, and is thus not suitable for general-purpose stereo display. With current display systems, there are no specific display issues other than the need to present moving video.

- **Volumetric displays:** In contrast to all types of two-view stereo displays, volumetric displays produce an image that actually takes up a three-dimensional volume. In recognition of this distinction, the individual image elements in a volumetric display are often called "voxels" (volumetric picture elements), in contrast to the "pixels" (picture elements) of a 2-D display. Methods to produce volumetric displays have included 1) mechanically scanned devices that either emit light or serve as a target for an energy source (light beam or electron beam) that causes emission at each voxel in turn, and 2) non-linear optical materials that emit light omnidirectionally at every point where two light beams from different sources intersect. Volumetric displays provide many different points of view simultaneously, allowing simultaneous viewing by multiple users, and allowing users to rapidly shift viewpoints by moving their heads. While two-view stereo displays can show an image of any arbitrary apparent size, volumetric displays are limited to depiction of objects no larger than the volume of the display. Display technology challenges include:
  - Transparency. Existing volumetric displays are arrays of luminous pixels, and do not provide a mechanism for hiding surfaces that would be hidden from a particular point of view if the objects depicted were opaque. Applications have tended to be limited to those for which the objects of interest have no significant volume, and it is their position in 3-D space that is important, such as air traffic control systems, and to those applications for which the transparency of the objects displayed is not a problem.
  - Display refresh rate, and the number of voxels that must be provided. In principle, a volumetric display with three-dimensional resolution comparable to that of a 2-D display would have hundreds of times as many image elements (or more) as a 2-D display. For any sort of reasonable display refresh rate, this implies that the image element data

must be transmitted and displayed at an enormous rate. Current volumetric displays have limited resolution, so this has not yet become a major problem, but it will become a major issue as volumetric display technology advances. Refresh rate in mechanically scanned volumetric displays is limited by the mechanical capabilities of the scanning mechanism, and (in air-filled displays) by wind resistance.

- **Holographic displays:** Holographic photography is in a fairly advanced state of development. A refreshable holographic display is theoretically possible, but the extremely high display resolution required and the enormous amount of information needed to represent a holographic image raise tremendous challenges in display design and data transfer. Extremely limited research on fully general holographic displays has been performed thus far, and has concentrated on displays a few millimeters on a side, but as information technology advances, it is expected that holographic displays will become an increasingly attractive option for 3-D display.

4. DISPLAY CHARACTERISTICS THAT LIMIT USEFULNESS FOR STEREO

Stereo photographers who use film must take the characteristics of their medium into account if they are to produce good quality stereo photographs. Similarly, producers of displays and content for 3-D presentation must take the characteristics of the displays and the display driving systems into account. The wide variety in display technologies and the many methods of displaying stereo make these issues more complex than the analogous issues for photographic film.

Across the many different display technologies, it is possible to come up with a generic set of display characteristics that affect usefulness for stereo. The importance of any particular characteristic, of course, depends on the display technology being used and on the method being used to present 3-D. A good general list is as follows:

- **Resolution:** All displays are limited in the image resolution they can present. It is conceivable that displays in the future will be limited only by the wavelengths of the light they use, but current systems have considerably coarser resolution, and the display configuration often has further influence on effective resolution. This raises a number of issues for 3-D presentation:
  - **Limit in useful field of view:** Unlike printers, which are usually rated in dots per inch, displays are typically rated in terms of the total horizontal and vertical resolution (or addressability) of the display, independent of display size. This is because high-resolution displays require the timely transport of large amounts of information, making the display characteristics from the viewpoint of the interface (total resolution) more critical than its characteristics from the viewpoint of the user (dots per inch, or apparent angular size of pixels). For a given display resolution, therefore, there are a limited number of pixels that must be distributed across the entire field of view. This means there must be a tradeoff between angular size of the pixels, and the total field of view.
  - **Limit in depth resolution ("depth planes"):** Stereo perception depends on relative horizontal displacement of objects in the left and right views. Perception of depth of extremely distant objects requires accurate depiction of extremely small horizontal shifts – down to and even exceeding the minimum imaging angular resolution of either eye. The limited resolution of displays therefore has the most pronounced effect on stereoscopic interpretation of distant parts of a scene. In the terminology of Ferwerda, the number of "depth planes" (number of different depths that can be distinguished by the user) is limited by the resolution of the displays used.
  - **Effects of color bars on stereo:** Many CRT displays employ triangular triads of phosphor dots to represent colors. Many modern color displays have approximately square pixels, composed of three vertical bars (or subpixels) in red, green, and blue. While this is a perfectly acceptable way of producing an image and presenting color, it is widely regarded as being one of the worst ways to utilize display resolution (in other words, a display of a given resolution will appear coarser or blockier with color bar pixel configuration than with other configurations, and a display that must have a given apparent resolution will require a higher physical resolution with this pixel configuration than with other configurations). As an additional issue for stereo, the sideways displacement of the red, green, and blue subpixels means that there will be a slight lateral shift in the brightness weighting (and therefore in the apparent horizontal position) of pixels based on the color being displayed. This can result in slight shifts in apparent depth, particularly of distant objects.
  - **"Jaggies":** A rectangular array of pixels can represent horizontal and vertical lines with great accuracy. Diagonal lines, curves, etc. must be represented in stairstep fashion, which may result in a visible jaggedness of lines and edges, and nonuniform apparent thickness of lines. These phenomena are frequently known in the display industry as "jaggies". The appearance of jaggies can be reduced by choice of subject displayed (not an acceptable solution for a general-purpose display system), by increasing the resolution of the display, or by various means of dithering (averaging or other combination of the values of adjacent pixels, thus reducing the sharpness of edges and transitions). Aside from esthetic issues, stereo vision makes considerable use of edges and transitions, and is therefore disproportionately affected by jaggies.

  - **Inaccuracies of geometric transformations:** Some stereo display methods employ geometric transformation of the images being viewed. Examples include correction for keystoning, and adjustment of the aspect ratio of side by side and top/bottom stereo pairs. If these transformations are performed computationally (by shifting the pixels in the images on the display), then limits in display resolution also affect the accuracy with which these transformations can be implemented. Inaccuracies in transformation can result in distortions of the stereo images, and retinal rivalry (particularly around the edges of the display area).
  - **Effects on resolution of geometric transformations:** Linear geometric transformations (for example, adjustment of aspect ratio) cause effective image resolution to be different in different directions (for example, horizontal resolution and vertical resolution may differ, as seen by the user in terms of angular size of image pixels). Non-linear transformations (as in anamorphic display systems) cause certain areas of the displayed image to have lower effective resolution than other areas. For a sufficiently high degree of geometric transformation and a sufficiently low display resolution, these effects can degrade the perceived quality of the stereo image.
  - **Positioning of images for effective use of pixels:** If a vertical line or edge (for example) of an image happens to line up with the natural distribution of pixels on a display, the line or edge will appear sharp and accurately rendered. With only a slight shift of the image relative to the pixels, the line or edge can appear blurred or smeared. If homologous features are sharp in one image and blurred in the other image, retinal rivalry can result. Some mapping algorithms (which can be incorporated in graphics control systems or display software) attempt to shift features relative to display pixels for advantageous display – this can result in slight distortions of a stereo image. For example, if a stereo depiction of a rectangle that is face-on to the user has one side shifted in one image but not shifted in the other image, the rectangle will appear in stereo to be slightly tilted (one side nearer to the user than the opposite side). If an image of fixed composition is to be shown on a display of known characteristics, deliberate placement of images may be used, but in the general case the only solution is a sufficiently high resolution.
- **Viewing angle and effects on image characteristics:** Viewing angle effects are based on display construction and materials properties, rather than on resolution. While an ideal display would appear the same brightness and color when viewed from any angle, many real-world displays exhibit significant shifts in both brightness and color when viewed from an angle other than the intended viewing angle, sometimes to the point of complete brightness and color reversal. These effects can be seen with both horizontal and vertical shift of viewing angle, depending on the design of the display. This can be a factor in stereo systems that put the two views on one display, as the angle of view of homologous points can be different for the two eyes.
- **Screen refresh rate and pixel response time:** Just as for 2-D presentation, screen refresh rate and pixel response time determine how fast the displayed image can change, and therefore how effective the display will be at presenting fast-moving video images. Displays that are particularly slow may be subject to "submarining" – an object that is moving against a stationary background seems to "disappear" or move behind the other objects being displayed until it stops moving, at which point it "reappears" or "surfaces". This may be somewhat more of an issue for 3-D than for 2-D because transient positioning affects relative size and depth of moving objects. Pixel turn-on time and turn-off time may be asymmetric, resulting in further shifts in apparent size of moving objects.
- **Time synchronization:** As described in the general overview of two-view stereo displays, synchronization between the homologous points in the left and right views is a function of frame refresh rate and refresh method, and the geometry by which the two views are presented on the display(s). If the left and right views are from separate video sources, this becomes an additional synchronization issue.
- **Matching of multiple displays:** Due to manufacturing variations, precision matching of multiple displays is extremely difficult. This is a challenge for the manufacture of two-display stereo systems, and also for "tiling" (connection of multiple displays to make a larger, higher resolution display system).
- **Image data storage/processing issues:** The methods used to represent images as data for a display inevitably lead to some loss of image quality, which, given the "closer to true life" nature of 3-D imagery, affects it even more than it affects 2-D display. A particular issue for stereo is the lossy compression algorithms that are frequently used to reduce storage and transmission requirements for images. While overall fidelity is generally acceptable for the 2-D images for which it was designed, compression of stereo images may be affected by several common characteristics of lossy compression algorithms:
  - The starting point from which the algorithm is applied can make a significant difference in the fine detail of the displayed image. Compression may use a block-based approach, and the registration of the left and right images with respect to the compression blocks may differ, resulting in detail differences and retinal rivalry.
  - Even if registration of left and right images with respect to compression blocks is the same, the slight differences between left and right images that make stereopsis possible may interact unfavorably with the compression algorithm, which was designed to optimize the preservation of large image features.

    - Compression algorithms commonly reduce the color resolution of the images, since this is one of the least noticeable features of a 2-D image. This may affect display systems using anaglyph and other color-based stereo methods.
- **Burn-in:** Displays that use emissive phosphors may be subject to a phenomenon known as burn-in, in which a particular pattern that the user displays for extended periods of time results in a permanent change in the phosphors, and a noticeable afterimage that shows up when something other than the usual pattern is displayed. This can be an issue when a display is used part time for two-image stereo, and part time for full-screen 2-D use, as the areas of the display that make up the left and right images (together with the areas that are not used in stereo mode) constitute a pattern, that may be visible in 2-D display mode. In the past, CRT displays were highly susceptible to burn-in (thus the tradition of using "screen savers" to prevent burn-in), but design advances in recent years have made them much less susceptible. Plasma displays, field emission displays (FEDs) and electroluminescent displays may exhibit burn-in.
- **General display characteristics:** There are many known display characteristics, used as a basis for evaluation and comparison of different displays. Examples are brightness, contrast, geometric distortion, and others that have been described in this section. Some of these characteristics have no specific connection to the issues of stereo displays, while others are significant. An example of the latter is mura, irregular patterns of relative brightness and darkness found across the faces of LCD displays, and different for every unit manufactured. Mura is specifically of interest to stereo because it can cause perceptible differences in the left and right images (whether they are shown on the same display or on two different displays), since the mura pattern will be different in the two images. The Video Electronics Standards Association (VESA) has produced a Flat Panel Display Measurement (FPDM) standard, which explains many display characteristics, and describes ways to measure them.
- **Digital video / HDTV issues:** The tremendous increase in the use of digital video (as in DVD systems) and the recent debut (in the US) of broadcast HDTV offer the potential for stereo, which could result in more widespread use of stereo in general. The digital video formats have a fixed set of characteristic features, and at least in concept have room for the inclusion of stereo format standards.

5. DISPLAY TECHNOLOGIES AND ISSUES FOR STEREO PRESENTATION

The following section is organized by display type, and discusses issues for each that are relevant to stereo display:

- **CRT (cathode ray tube):** CRTs are a very mature technology, and have the advantage of having been used extensively for stereo display, so their characteristics relevant to stereo are well known. CRTs are not pixel addressed – there is no fixed correlation between the logical pixels and the phosphor dots on the screen, and any given logical pixel generally illuminates a number of adjacent phosphor triads to varying degrees. CRTs thus have very little tendency to show jagged lines ("jaggies"), and edges and lines are less sharp than for other displays of comparable resolution. Because they are driven by a sweeping electron beam, significant geometric distortions (e.g. straight lines appearing curved) are sometimes present – many displays are user-adjustable to compensate for these distortions. CRT phosphors may be slightly susceptible to burn-in. Frame refresh rate can be very high in high-end models, and pixel response is usually fast, but designers can use a different phosphor for slow pixel response.
- **LCD (liquid crystal display):** LCDs are pixel addressed displays with distinct pixels, and thus subject to the "jaggies" and image placement issues. They produce sharp edges and distinct lines in the images displayed. Some LCDs are susceptible to crosstalk, or "ghosting" – electrical connections among the pixels can cause faint horizontal and/or vertical lines to extend beyond displayed objects. As discussed in the section on display characteristics, mura can potentially produce retinal rivalry between the left and right images of a stereo pair. Usable viewing angle is usually more limited than for emissive technologies. LCD displays have a wide range of pixel response times, but most displays with red, green, and blue subpixels do not use a frame refresh faster than 60 Hz, and flicker is not usually a significant problem with 2-D LCD displays. It is possible to use LCDs for sequential frame stereo, but not generally at the high frame rates possible with CRT displays. Some LCDs, particularly small ones for head mounted displays, use color sequencing: e.g. the same physical pixels are used for all three colors, the display runs at 180 Hz, and the backlight flashes a sequence of red, green, and blue in successive frames, with the effective result of a full color image refreshed at 60 Hz. There are several common types of LCD displays, with distinct characteristics:
    - **Passive matrix (PMLCD or STN):** In general, passive matrix displays have relatively low contrast, slow pixel response time, narrow viewing angle, and a tendency to show crosstalk. They are widely used in applications where low cost and low power consumption are at a premium.
    - **Active matrix (AMLCD or TFT):** Active matrix displays usually have faster pixel response times in comparison to passive matrix displays, higher contrast, wider viewing angle, and little tendency to show crosstalk.
    - **Cholesteric displays:** Cholesteric displays are a reflective technology, characterized by slow frame refresh rate and slow pixel response time (unsuitable for moving images), and the ability to hold an image for long periods of time

without application of power after the initial write. They are usually targeted for applications such as signs, electronic books and newspapers.

- **Plasma displays:** Plasma physics favors the use of relatively large pixels, so plasma technology is usually applied to large area displays. Display phosphors are somewhat susceptible to burn-in. Existing commercial displays have frame refresh around 60 Hz, and utilize pixels that are either full-on or full-off during any given frame period. Grayscales (referring to both black-and-white and color shades) are therefore achieved by means of cyclical spatial modulation, controlled by the panel electronics. The repeating patterns of pixels can result in a visible "swimming" motion on the display, which is noticeable when the user gets close to the display, and is more noticeable for some grayscales than for others. This swimming pattern can potentially result in retinal rivalry for stereo applications.
- **Direct view microdisplays:** When two microdisplays are mounted (as in a headset) for stereo viewing, issues include obtaining a sufficiently close match between two displays during manufacture, and the geometry of a two-display system (interocular, registration of pixels, and so on).
- **Direct retinal scan displays:** Retinal scan displays are starting to make an appearance (at present, predominantly in the military market), and may become more common in the future. The basic principle is that a scanning laser shines through the pupil of the eye and draws an image on the retina. The image is motionless with respect to the writing apparatus, so it does not shift with motion of the eye. This display technology can in principle be used for stereo, though the authors are not aware of any such application to date. Display matching and registration issues would be comparable to those of direct view microdisplays.
- **Micromirror displays:** Micromirrors are a reflective display technology, typically used for screen projection or for rear projection in an enclosed box. There is a separate mirror for each pixel (or subpixel), with two positions: ON and OFF. Grayscales are achieved by altering the duty cycles of the mirrors to achieve temporal modulation. The mirrors have extremely fast response time, so temporal modulation is usually performed within each frame refresh period, with a "bit splitting" algorithm to even out the distribution of mirror activity over the frame period and thus avoid unintended flashes of brightness in the image. Micromirror displays can be used like other stereo projection systems. High end projection systems use two or three mirror arrays for different colors, while low end displays use a single mirror array and a "color wheel" (wheel with different colored filters) to provide color sequencing. As with other color sequencing displays, frame rate and synchronization are issues for stereo use of displays with color wheels.
- **3D transmission standards:** There has been limited progress thus far on widely accepted storage, transmission, and interface standards for 3-D display. The JPS file format defines a standard for storage of stereo still images. Standards from the Video Electronics Standards Association define an interface for a sync signal to be used with sequential frame/field stereo. There has been some work on methods of storing and transmitting stereo images as a single 2-D image signal and a "difference" signal, allowing reconstruction of left and right views from what may require only slightly more storage than a 2-D image. Future stereo display systems may follow a standard for transmission and synchronization of two separate video streams for left and right views.

6. MATCHING OF DISPLAY / PRESENTATION TECHNIQUE / SUBJECT

Given the listing of display issues for stereo, the general characteristics of different display types, and general issues for display subjects, it is possible to come up with general guidelines for matches among display type, presentation technique, and stereo subject. Specific choices still rely to some extent on measurement of the specific devices involved – it is part of this ongoing research to derive more specific weighting of the relative importance of the different display parameters, for example whether color bar design or pixel response time is likely to be more of an issue for side by side stereo pairs, so the system designer or user, knowing what to look for, can concentrate on the parameters that are most likely to be critical. It is likely that any given matching will produce two or three combinations that stand out above the others – this allows the designer to add other criteria to the selection, such as cost, and versatility for multiple uses.

The following is a general classification of subjects to be displayed, with respect to stereo display issues:

- Amount of depth in the subject, particularly distant parts for which depth interpretation is critical to the subject: If multiple distant "depth planes" are required for the subjects to be shown, then display resolution will be a critical issue.
- Degree of importance of preserving geometry: If the preservation of exact geometry is critical, then important issues include resolution, geometric distortion, and possibly storage method and pixel registration.
- Amount of motion in the scene: If the scene includes rapid motion, then frame refresh rate, pixel response time, and left-right image synchronization will be important, while method of grayscale representation will be of less importance (since time-dependent artifacts will not be as noticeable in the presence of motion). If the display uses color sequencing, then motion in the scene may result in significant color artifacts.

- Color composition of the subject: The colors (and distribution of colors) of the subject may affect the ability to use color-based separation, and may result in shifts in relative depth if the display uses color bars as subpixels and if display resolution is insufficiently high.
- Interaction of subject and viewing conditions: The combination of the subject matter to be displayed in stereo and the expected viewing conditions can profoundly influence the selection of display and presentation technique. As an example, bright ambient conditions increase the visibility of flicker in a display, and motion of a subject emphasizes synchronization issues in the presence of low frame refresh rate, so a user who expects to view moving images in bright ambient conditions should either avoid sequential frame stereo, or choose a sufficiently high frame rate to avoid flicker and synchronization effects.

7. DETECTION AND IDENTIFICATION OF NEW DISPLAY CHARACTERISTICS

The Advanced Display Technology Systems laboratory at the National Institute of Standards and Technology (NIST) has a project to characterize different display technologies, and to define their usability for a variety of applications. Part of this project deals with known display characteristics, and part deals with the detection and identification of new or previously unknown display characteristics. The continuing evolution of display technology and the continuing development of new and increasingly demanding display applications mean that new display artifacts will continue to surface, artifacts being defined as instances in which the subject displayed differs in some significant way from what was supposed to be displayed. Artifacts may be easily detectable (for example crosstalk, poor image contrast, or major stereo synchronization problems), or they may be difficult to detect – subliminal effects can interfere with correct interpretation of a display, or lead to eyestrain, headache, and so on. The detection of artifacts is particularly important for applications where displays are being used for purposes other than what was originally intended, for example stereo display systems that use 2-D displays as components.

The display characterization project has been gathering a variety of signal sources, to represent different applications, and a collection of different technology displays, including advanced CRT, active matrix- passive matrix- and cholesteric LCD, plasma, micromirror projector, and field emission. Displays are being driven by the different signal sources, and advanced image processing algorithms used to detect spatial and time-based artifacts. The artifacts detected, together with analysis of their causes and effects, will be made available to industry, from which it is hoped that the field of display metrology will be advanced, serving as a guide to display users and as a driver for development of improved displays in the future. Because stereo display has an important role to play in the future, artifacts related to stereo display will be an important area of concentration in this research.

8. OPTIMIZATION OF FUTURE STEREO DISPLAYS, AND INCREASING STEREO USAGE

Stereo imagery utilizes more parts of the visual interpretation centers of the brain than conventional 2-D imagery, and if not done correctly is more likely to lead to problems in interpretation, eyestrain, and so on. It is therefore critically important that stereo applications make the best use of display technology and presentation techniques. By using this approach, the user community and the public in general will be exposed to good applications of stereo, allowing the benefits of stereo to be properly appreciated, and encouraging the more widespread use of stereo.

With an increased push to use stereo, knowledge of the key issues for stereo display, and the information that is being collected on the relative importance of these issues for different applications, will help to drive the development of improved display systems that have stereo application as an original design goal. This will further enable the development and use of good stereo applications, ideally creating a positive feedback loop in display development, that will ultimately result in the ability to use stereo wherever it makes sense to do so.

9. SUMMARY

Displays will become an increasingly important format for stereo presentation, and stereo will become an increasingly important part of the role of displays. To facilitate the smooth progression of these trends, it is useful to think of stereo display systems in terms of their underlying display characteristics, and how these characteristics interact with the methods of presenting stereo, the display demands of the subjects that are commonly presented in stereo, and the characteristics of human stereo vision. This paper has outlined human visual requirements from a display perspective, general methods of stereo presentation in terms of displays, key display issues for stereo presentation, display technologies as they relate to stereo display, and general guidelines for matching display, presentation style, and subject matter. Ongoing research at NIST is seeking to provide a more quantitative analysis of these issues to permit more direct ranking of priorities, and to detect and identify new display artifacts that affect applications such as stereo.

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[i] Correspondence: Email: john.roberts@nist.gov; Phone: 301-975-5683; Fax 301-869-7429; http://www.nist.gov