STEREOSCOPIC DISPLAY USING A 1.2-M DIAMETER STRETCHABLE MEMBRANE MIRROR

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ABSTRACT

A glasses-free stereoscopic display has been developed in which a large diameter concave Stretchable Membrane Mirror (SMM) is used both as a viewing screen and optical element. SMMs offer considerable advantages over traditional imaging optics in terms of reduced weight and cost, and are revolutionary in their ability to vary their radius of curvature to give a wide range of mirror f/Nos. (from optically flat to around f/1 using current membranes). This is achieved by controlling the magnitude of an applied pressure difference which acts over an edge clamped metallised polyester membrane, forming the basis of a SMM. A stereoscopic display has been developed in which a 1.2-m diameter SMM is used. Stereo pairs are projected at the surface of the mirror and viewed through a pair of virtual viewing windows (real images of the projection lenses that are generated by the SMM). Such a configuration minimises light loss, giving a very bright image against the specular reflecting surface of the SMM. The image can be formed in front/on/behind the plane of the SMM, making both real and very large sized virtual images possible. Several formats ranging from simple stereo photographs to live stereo video feed in a telepresence display have been viewed using this system.

Keywords: stereoscopic display, membrane mirror, three-dimensional imaging, telepresence, projection display.

1. INTRODUCTION

With stereoscopic systems the viewer is presented with two distinct images of a 3-D scene, one 2-D image corresponding to the left eye view and the other corresponding to the right eye view. Production of the stereo images is achieved by recording the scene from a slightly different lateral perspective for each view; providing the required binocular disparity. The 2-D images are presented in such a way that the viewer sees the left eye image with the left eye and the right eye image with the right eye. When viewed, the two 2-D images are merged in the brain to form a 3-D view of the scene. Image separation is generally achieved either by the anaglyph or field-sequential method. Polarising and colour anaglyph techniques rely on the use of polarising and colour filters respectively to ensure that each eye receives the correct image. Field sequential techniques rely on presenting the two stereo images at different points in time and ensuring that the light is prevented from reaching, say, the left eye when the right eye image is being presented. Most professional workstation environments use this technology. Liquid crystal shutters may be attached directly to the front of the monitor, using passive polarised glasses to separate the images, or the shutters can be incorporated directly into the viewing glasses. The final, and simplest, method of separating right and left eye views is to use fixed optics to direct the images to the viewer. The classic Wheatstone and Brewster stereoscopes are examples of this type of display, with the View-Master stereoscope being a modern day equivalent that uses separate lenses to view the stereo slides. These displays are similar to the stereoscopic display to be described in the following section in that a fixed optic, namely a SMM, is used to separate the left and right eye images, with the advantage that there is no requirement for special headsets or viewing glasses.

There have been many different projection-type 3-D displays over the years, using both direction-selective and autocollimating (retroreflecting) screens[1]. The use of a large concave mirror as a direction-selective screen in 3-D display

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has previously been proposed by Minter[2]. Minter's system directs light from two separate projectors, each displaying a different stereo view, to the viewer via a large beamsplitter and concave mirror. The curvature of the mirror keeps the stereo pairs separate. More recent patents by Adler[3] and Kempf[4], also using a large concave mirror as a directional screen, illustrate the continuing interest in this type of display. Use of a retroreflecting screen as an alternative to a concave mirror is the principal behind an autostereoscopic display developed by Xenotech, Perth, West Australia[5]. Projectors provide the stereo images, with a large beam splitter being used to direct the light onto the retroreflecting screen. The screen returns the light along the same path, enabling the light transmitted through the beam splitter, placed at 45^0 to the screen, to reach the viewer. A video camera is used to track the observer, with moveable projectors ensuring that the correct stereo images are seen by the viewer. Retro-reflecting screen systems have the advantage over mirror systems in that the projector light is returned to source, regardless of distance from screen. A concave mirror system is more restricted in that light is only retro-reflected when the projector / viewer(s) are located at the mirror radius of curvature. A retroreflecting screen, whilst cheaper to manufacture than conventional large diameter concave mirrors, will not give the same optical performance; grainy images and significant light loss due to the requirement for a beam splitter and scattering of light at the screen surface are a few of the main disadvantages of such systems.

2. STEREOSCOPIC DISPLAY USING A STRETCHABLE MEMBRANE MIRROR

The glasses-free stereoscopic display system developed at the University of Strathclyde enables the viewer to see a variety of image formats in 3-D. The supported formats include stereo photographs, 35-mm slide projections, computer generated stereo pairs and live feed stereo images from remote cameras. The primary viewing element used is a 1.2-m diameter membrane mirror, reference figure 1. Specific advantages of the system include:

- No requirement for special headsets or viewing glasses.
- Very bright image due to optical configuration used and viewing screen's specular reflecting surface.
- Large sized images (determined by mirror aperture).
- Ability to accurately position the image plane in space.
- Continuous display of stereo images (non-field sequential).

Figure 1: 1.2-m diameter stretchable membrane mirror.

A SMM is simply a sheet of metallised plastic which is stretched over a specially shaped circular frame. The material used for the mirrors is polyethylene terephthalate (PET), a polyester film made by Dupont under the trade name Mylar. The Mylar film is then aluminised by a process of vacuum deposition. Membranes used on the mirrors are typically around 125-μm thick. Once clamped, the membrane is stretched over a circular frame and tensioned. The tensioning process, if correctly designed and used, serves two purposes: Firstly, it provides a symmetrical membrane tension, ensuring that when the mirror is deformed under load it retains a high degree of symmetry. This is necessary to ensure good image quality and membrane stability. Secondly, to provide a vacuum seal around the contact area between membrane and frame. A vacuum source is connected to the mirror in order to remove air from the cavity behind the membrane. As the air is removed, the resulting air pressure difference forces the mirror membrane back into a concave shape. The concave profile now acts as a focusing, imaging mirror. Controlling the magnitude of the applied partial vacuum, and hence pressure difference acting over the membrane, now controls the curvature, and therefore focal length, of the mirror. Since the early 1980's there have been many different concave membrane mirror designs. In 1984, one of the authors published what is believed to be the first focused white light images from plastic membrane mirrors[6]. Although published in 1984, superb white light images were produced as early as 1983 using stretchable mirrors constructed at the University of Strathclyde; an undergraduate thesis bears testament to this fact. The current mirrors may be used over a wide range of f Nos., from perfectly flat down to around f/1.

Figure 2 shows the stereoscopic display system developed at the University of Strathclyde. Left and right eye views are presented using monitors, photographs or projection screens placed on either side of a central lens assembly. Two monitors are shown in figure 2. Two lenses project the left and right eye views towards the mirror. The size and position of the projected stereo pairs is determined by the focal length of the lenses and the relative position of the monitors. The projected image plane can be behind, in front, or on the plane of the stretchable mirror. The stretchable mirror is used as a directional screen, creating a real image of the lens assembly such that the left and right eye views remain separated without the chance of cross talk. Looking through the real image of the left and right eye lenses gives a 3-D image. Essentially the system produces a pair of circular viewing windows, one for each eye, through which the viewer must look in order to see the stereo pair.

The lenses used are 65-mm in diameter, giving a distance between centres equal to the average inter-ocular separation. The viewing windows are created by first producing a virtual image of the lenses using a pair of front silvered plane mirrors at 45^0 to the optical axis of the mirror. The virtual image now has the lenses side by side, ready for imaging by the stretchable mirror. Arranging for the virtual image of the lenses to be just inside the mirror's radius of curvature means that the resulting real image will be slightly magnified and projected past the mirror radius of curvature. This allows for a more comfortable viewing position. The slight magnification of the resulting real image not only improves the allowable head movement, but the added separation between user and lens assembly also provides valuable workspace for, say, using a mouse and keyboard for interacting with the display. The SMM operates at approximately f/1.3, giving a wide field of view and enabling a compact display.

The system is clearly a single user display. Slight head movement is possible due to the aperture of the viewing windows, but the system is essentially a fixed viewing position display. This has some useful advantages. There is only one viewing position and so it is a very simple display to use. Once the user is in the correct head position, the stereo images are automatically presented to each eye. Experience showed that users of the system were able to align themselves correctly and see in 3-D within a very short period of time. With free viewing, for example, although the viewer may be in the correct position, there is still a considerable learning curve before the viewer learns how to adjust convergence and accommodation separately to enable a 3-D scene to be viewed. Parallax barrier and lenticular sheet systems can also be difficult to view. Pseudoscopic images result if the viewer is positioned such that the left eye image goes to the right eye and vice versa. This cannot happen with the above stereoscopic display. Positioning the viewer's head such that the left eye sees the right eye image would mean that the right eye was outside the viewing zone, and hence would be unable to see any image.

The image plane of the projected stereo pairs can be in front / on / behind the plane of the SMM, enabling both real and virtual images to be formed. Real images are seen to sit out from the plane of the mirror, giving the appearance of an object floating in space between the viewer and the screen, whereas a virtual image sits behind the plane of the mirror. As in holography, creating a virtual image enables life-sized 3-D scenes to be viewed as the mirror acts as a porthole through which the scene is viewed. Since two mirror reflections are involved, one from the plane mirror and one from the SMM, there are two left-hand to right-hand coordinate transformations which cancel. Simply rotating the display monitors by 180^0 ensures that the 3-D image is the correct way round, making text readable.

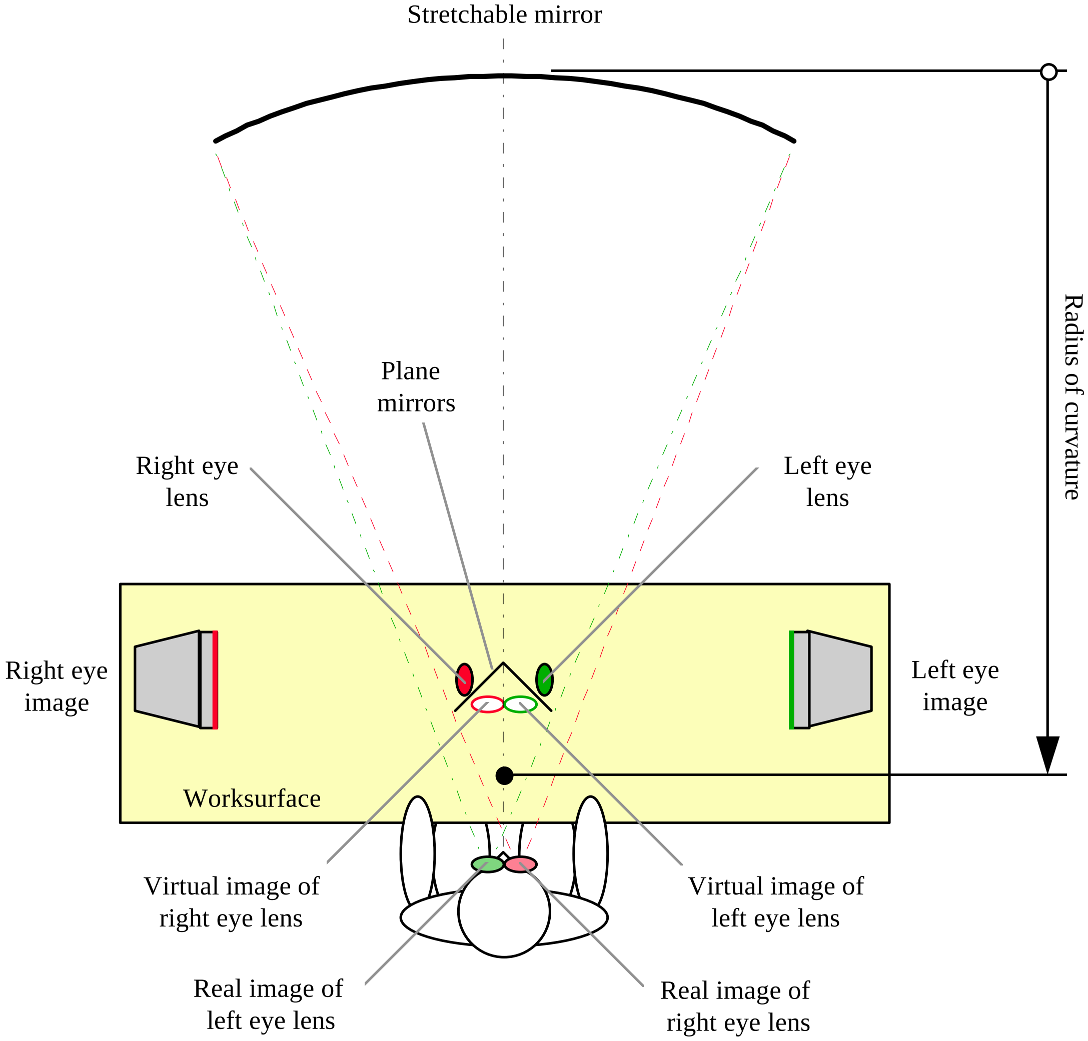
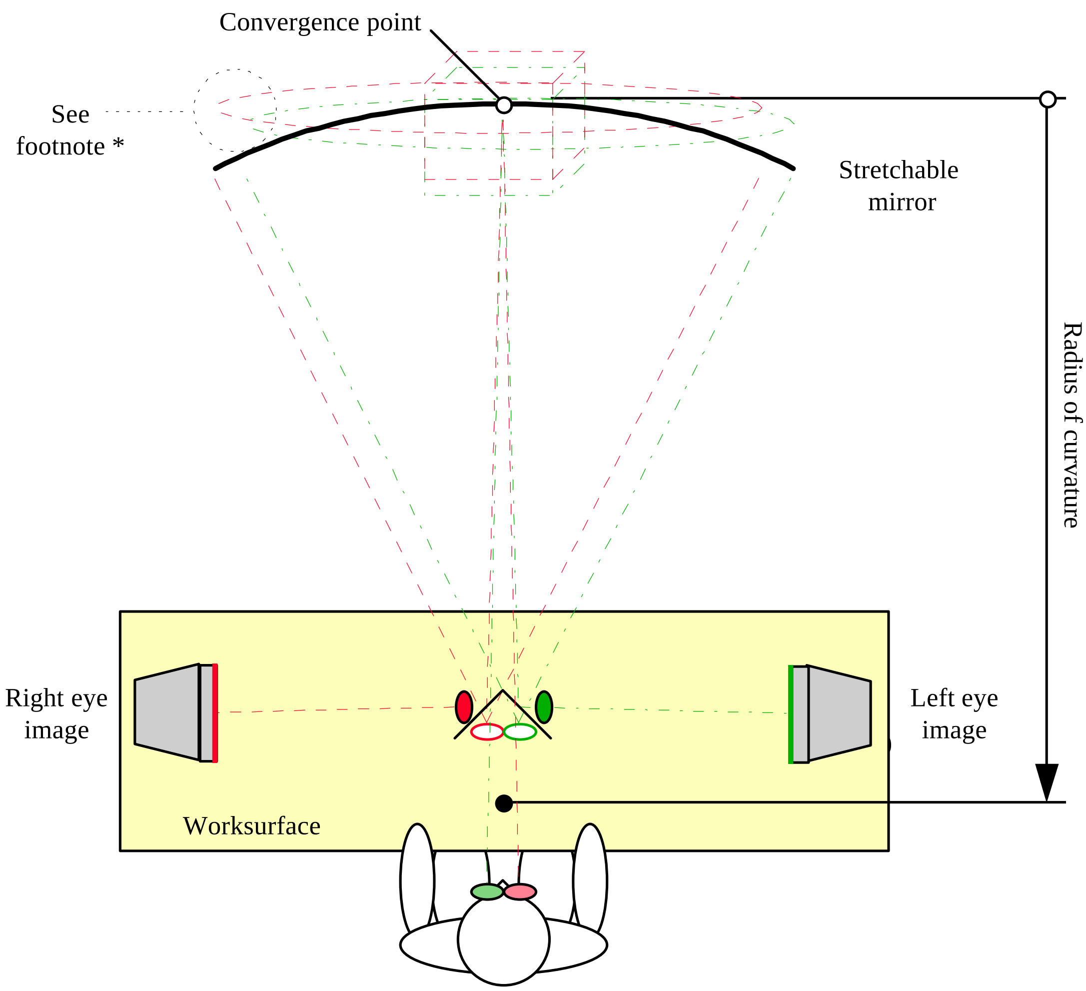


Figure 2: Stereoscopic display system using stretchable mirror.

Being able to control the position of the final image plane enables the accommodation - convergence relationship to be varied. The further away the image plane, the smaller the required degree of convergence, and hence the easier the resulting image is to see. The eyes are also focusing at a greater distance, and so viewing is more relaxed. The discrepancy in the convergence-accommodation relationship becomes less pronounced the further away the image plane is. It is this disparity in physiological depth cues that makes free viewing stereo images difficult for some viewers. In cross viewing, for example, the user has to focus on a plane some way beyond the convergence point. Independent control over convergence in the above display enables the correct accommodation - convergence relationship to be attained; enabling the viewer to focus and converge on a single image plane. Reducing the disparity in the accommodation - convergence relationship can greatly assist stereo viewing, enabling extended use with reduced risk of eye strain. The system is configured by displaying two grid images on the monitors and, by changing their location on the screen, noting the required position to cause the projected image of the grids to overlap on the surface of the mirror. Several viewer's who had experienced field sequential stereoscopic displays using shutter glasses commented on how comfortable and simple the above system was to use. They also commented on the comparative improvement in image sharpness and brightness with the mirror display. In terms of image flicker and resolution, because two separate screens are used to present individual stereo pairs, the resulting image has twice the resolution of a similar single screen spatially multiplexed display and does not have to be viewed through a continually modulating screen. As with all stereoscopic displays, the accommodation-convergence relationship breaks down when viewing the scene contained in the 3-D image. Convergence, but not accommodation, changes when looking at, say, the background image compared to the foreground. Figure 3 illustrates how the correct accommodation - convergence relationship is achieved by overlapping the left and right eye images on the plane of the mirror.



* - Difference in image planes shown to aid viewing. Image planes are coincident in reality

Lateral shift in monitor position to ensure convergence and focal point are coincident

Figure 3

Stereoscopic displays using static images have been developed. These systems basically consisted of stereo pairs being imaged through a lens-mirror assembly similar to that shown previously. Stereo photographs were created by taking two photographs of a scene from slightly different perspectives. The photographs were then physically attached to a screen where they were then viewed through the stereoscopic display. An improvement was to create slides of the photographs such that the image could be projected onto the screen, enabling the size of the image to be scaled so that the final image filled the full mirror. Figure 4 illustrates a schematic of the projector fed stereoscopic display.

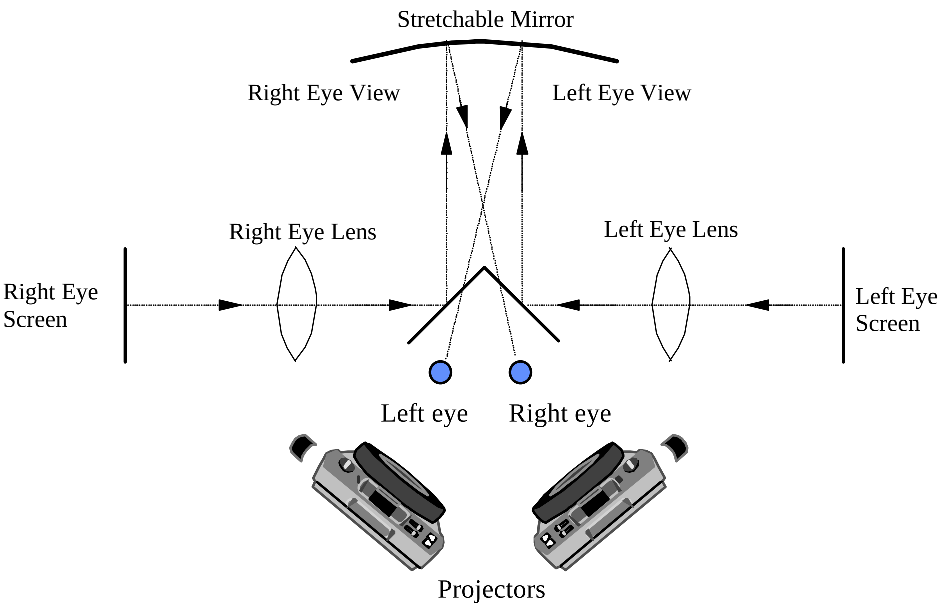


Figure 4: Projector driven stereoscopic display.

Motion parallax is a particular advantage of autostereoscopic displays. The ability to change viewing position and see a different perspective view greatly enhances the visual effect. The above technique for viewing stereo pairs has a fixed viewing position, and so motion parallax is not available. By using real-time computer generated stereo pairs of live feed video, however, the ability to look round the object being viewed is restored. The user's head remains static, but the viewpoint may still be changed by software or by physically moving the location of the stereo cameras used to relay live video of a 3-D scene. The following sections describe how computer generated and live feed stereo pairs were used to create a dynamic, real-time, stereoscopic display system using a SMM.

2.1 Real-Time Stereoscopic Display using Live Video Feed

One interesting area of use for stereoscopic displays is telepresence. Telepresence enables an observer to view a remote location in 3-D by using a live stereo video feed. This technique is employed in applications such as underwater remotely operated vehicles (ROVs), where the added depth cues generated by a stereoscopic display can greatly improve the accuracy of vehicle positioning[7]. Any stereoscopic display can be used for this type of system. All that is required is a live video feed for both left and right eyes. Fibre optic feeds and compression techniques enable video signals to be sent over great distances. The Transparent Telepresence Research Group (TTRG), also based at the University of Strathclyde, recently demonstrated the first ever trans-atlantic video transmission over mobile phones to an audience at Photonics East 98[8]. As an alternative to conventional VR headsets, the SMM stereoscopic display has been successfully used as a large format, glasses-free, viewer for a remote, anthropomorphic robot head based, telepresence system; also developed by TTRG[9].

Two small CCD cameras are used in the SMM stereoscopic display, their lenses being separated by 65-mm to produce the required binocular disparity. Convergence and accommodation was fixed due to the fixed-focus camera lenses and static mounts used to hold the cameras. By using a fixed-focus, large f No., camera lens, the resulting image had a large depth of field. This meant that objects placed anywhere from a few hundred millimetres to several metres from the camera assembly remained in focus. Eventually objects did go out of focus, but this just added to the perception of depth since in reality objects generally do become smaller, duller, and have poorer contrast the further away they are from the viewer. The system was tested with a range of convergence angles, ranging from parallel viewing (zero convergence) to exaggerated cross viewing with the convergence point only a few inches from the front of the cameras. Obviously the ideal situation would be to have active cameras whose convergence and focus could be continually adjusted such that the convergence point and focal distance was on the same plane; just as with the human visual system. It was arranged for the cameras to converge at a distance equal to the viewing distance from the display screen. A converged camera setting has been shown to introduce image distortions in stereoscopic displays[10]. Despite these recognised problems, this configuration was still chosen for its simplicity in this prototype system. In future, parallel cameras with laterally shifted CCD sensors will be used to eliminate keystone distortion and depth plane curvature. Motion parallax was achieved in the first instance by moving an object within the field of view of both cameras. The display was greatly enhanced by the dynamic nature of the live video feed. The simple action of people moving about in the remote offices immediately introduces a form of motion parallax to the display. The stretchable mirror was essentially providing a porthole to this remote environment. The majority of the office seemed to form behind the plane of the mirror. It was not until the subject approached the cameras that a real image of the scene was produced. The closer the subject came to the camera, the further out the image seemed to come from the plane of the mirror. The exaggerated perspective was quite alarming, especially if the subject reached in towards the cameras. As the subject reaches toward the cameras, a hand simultaneously appears to reach out from the plane of the mirror. At this point the viewer has to consciously adjust convergence in order to form an image of the hand that is now sitting several metres out from the plane of the mirror. At this degree of convergence, viewing becomes uncomfortable. Generally, it was found that virtual images, regardless of how far they extended behind the plane of the mirror, could be viewed comfortably. Prolonged viewing of real images projected much beyond 1-m from the front of the mirror soon resulted in eyestrain.

Figure 5 shows how, for a fixed object position, the camera convergence point determines whether the resulting 3-D image is real or virtual. The optical configuration used, described previously in figure 2, projects the stereo images on the plane of the mirror. The correct accommodation - convergence relationship is, therefore, maintained by arranging for the default viewer convergence point to also be on the plane of the mirror.

2.2 Interactive, Real-Time, Computer Generated Stereoscopic Display

The computer generated stereoscopic display system was driven using a Silicon Graphics Onyx workstation with a Multi-Channel Option (MCO) enabling multiple monitors to be driven in parallel. Two monitors were used to display the left and right eye stereo views. The optical configuration used was the same as that shown previously in figure 2. The great advantage of the computer generated stereo pairs was the ability to change, by software alone, a range of parameters affecting the display. Real-time manipulation of the CAD model introduced a degree of motion parallax into the display. The fully rendered surface models used were extremely life-like, providing a wide range of psychological depth cues. ICEM Surf surface modelling software was used to drive the system (http://www.icem.com). The stereo facility was an in-built feature of the package, and so no further work had to be carried out in terms of software development. Maximum display resolution was 1280 x 1024. The lens system used was the same as that described previously, and used 800-mm focal length achromats as the projection lenses, giving approximately a 3:1 image magnification for a lens positioned at 3300-mm from the mirror so that the image of the screen was on the plane of the mirror.

Figure 6 illustrates the principal variables used to display stereo views within ICEM Surf. Modifying the stereo view parameters only changed the right eye view, the left eye viewpoint remaining fixed. The view reference point is by default the point in the 3-D world which is in the middle of the viewing volume (frustum). Separation is the difference in view points at the viewing plane, and so defaults to zero. Eye distance is the lateral spacing between eyes. Increasing eye distance shifts the right eye to the right. The viewing plane, like the object, is fixed at the centre of the view volume, and so increasing separation results in a view reference point towards the rear of the object. Parallel viewing is achieved when separation equals eye distance.

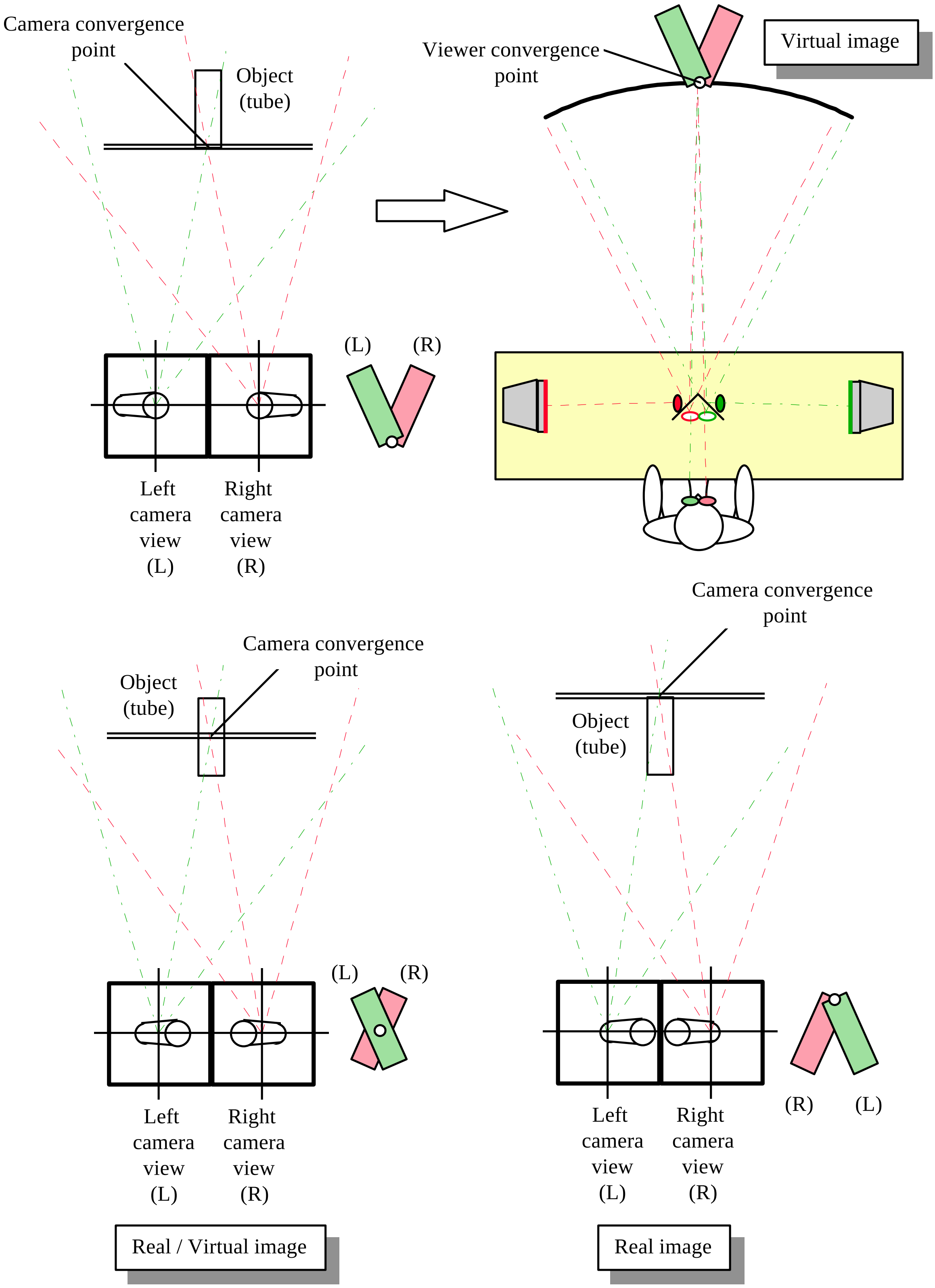


Figure 5: Relationship between camera convergence point on object and position of final 3-D image on screen.

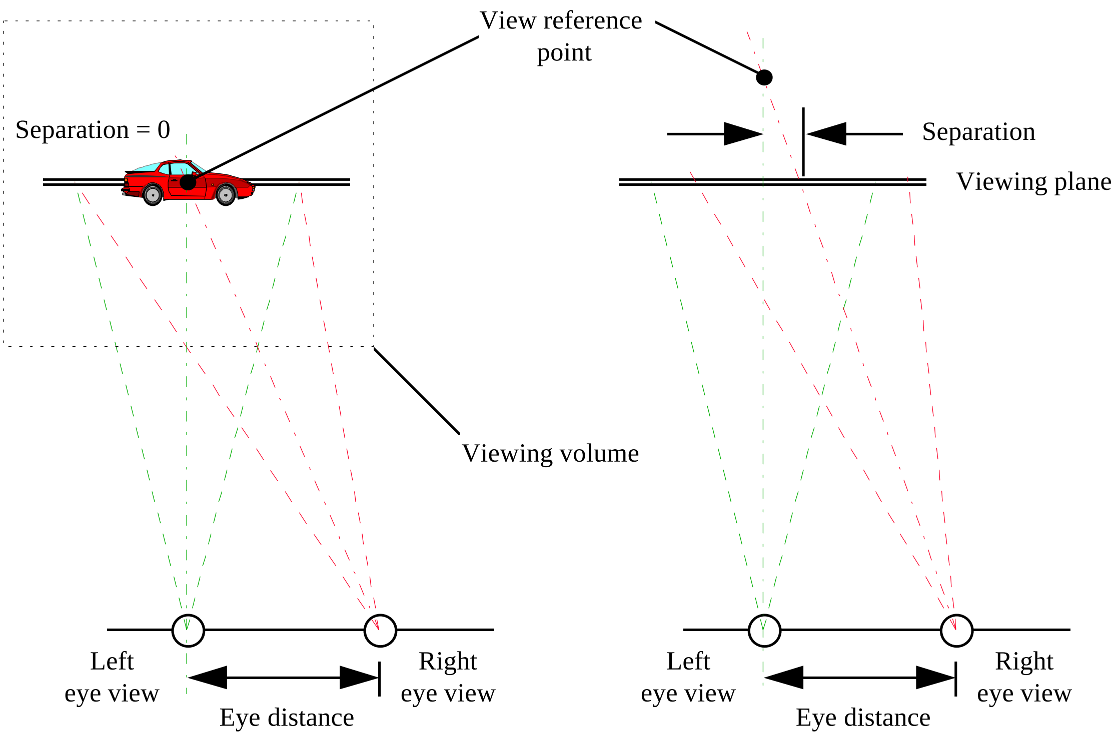


Figure 6: Variables used to define stereo views in ICEM Surf.

Initially a grid pattern is displayed on both monitors. The position of the image on the screen is changed until the observed grid patterns merge on the surface of the mirror. Since the image plane is on the plane of the mirror, the location of the view reference point will always be on the surface of the mirror. Those parts of the CAD model lying inside the view reference point will be replayed through the stereoscopic display as a real image, with parts of the CAD model lying beyond the view reference point observed as a virtual image. Replaying stereo images created with separation equal to zero will always result in the observed 3-D image lying in the plane of the mirror; the front and rear of the car being a real and virtual image respectively. In this configuration, model rotation is about the centrally located view reference point, and so the front of the car would be seen to move behind the plane of the mirror as the rear comes out towards the viewer. In practice, a small amount of separation was used to increase the percentage of the car being viewed as a real image. Zooming in on the model resulted in the magnified portion of the car coming out from the mirror towards the viewer. Zooming in or out on the CAD model changes the camera location relative to the view reference point. For a given eye distance, since the view reference point is fixed, the camera convergence increases as the cameras get closer to the model. This is the primary difference between this system and the previously described static camera stereoscopic display. In the previous system camera convergence was fixed. The computer generated stereoscopic display results in a more realistic and more comfortably viewed display since in reality a viewer's convergence increases the closer they move to the object being viewed. This process is replicated by ICEM Surf's stereo facility.

The system was used to produce 3-D stereoscopic images filling the full aperture of the stretchable mirror. Real images several metres out from the plane of the mirror were observed. With separation equal to zero, the view reference point was anchored at the centre of the viewing volume. Since the CAD model is rotated and scaled about this point, the resulting 3-D image was always centred on the plane of the mirror. Varying the eye distance or separation had the effect of moving the spatial location of the resulting 3-D image. Through software alone, the displayed image could be behind, in front, or on the plane of the stretchable mirror. As with the fixed camera stereoscopic display, real images much beyond a metre or so in front of the plane of the mirror were not very relaxing to view due to the increased disparity in the accommodation - convergence relationship. This could, of course, be rectified by arranging for the projected image plane of the stereo pairs to be in front of the stretchable mirror (achieved by moving the monitors closer to the lens assembly). A view reference point in the centre of the model would now centre the 3-D image on the new image plane in front of the mirror. The resulting image would not only be further out from the plane of the mirror, but the disparity between viewer focal distance and convergence point would also be reduced; making viewing the real image much more comfortable.

3. DISCUSSION AND CONCLUSION

The SMMs do suffer from spherical aberration at small f Nos., and so only around 80% of the mirror aperture could be used for imaging. Work is underway to model the nonlinear load-deformation response of the SMM using finite element analysis. It is hoped that a combination of boundary condition changes and / or new membrane material development will lead to a significant improvement in terms of mirror profile and hence useable aperture. Even with an aspherical, albeit symmetrical, mirror surface, the quality of results obtained were still very impressive. The quality of the imaging lens is important, but the optical quality of the mirror is not so important because the mirror is being used more as a light gatherer and a screen against which to view the image (especially if the final image is on the plane of the mirror). It was noted by several users that viewing the 3-D image against the specular reflecting surface of the stretchable mirror appeared to enhance the overall image quality. The fact that the specular surface does not scatter the light like a standard projection screen, but rather reflects it, is one likely reason for this observation. By returning all the reflected light to the viewer's eye, the resulting image is very bright and easily viewable in daylight. Diffuse or poorly reflecting surfaces tend to introduce a grainy quality to the resultant image, and so the quality of the mirror surface directly affects the quality of the final image. It was further noted that a magnified screen image did not suffer from obvious pixelation. Even screen images displayed at very low resolution still produced acceptable 3-D images even after being magnified several times. One proposed reason for this was that, far from being due to the quality of the mirror surface, the distortion in the mirror profile actually causes a defocusing of the image, thereby blurring adjacent pixels to create the impression of a higher resolution output image. The reason for the apparent improvement in image quality when viewed through a mirror is probably a combination of the above factors.

ACKNOWLEDGEMENTS

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