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Invited Paper

FELIX
A volumetric 3D laser display

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ABSTRACT

In this paper, an innovative approach of a true 3D image presentation in a space filling, volumetric laser display will be described. The introduced prototype system is based on a moving target screen that sweeps the display volume. Net result is the optical equivalent of a three-dimensional array of image points illuminated to form a model of the object which occupies a physical space. Wireframe graphics are presented within the display volume which a group of people can walk around and examine simultaneously from nearly any orientation and without any visual aids. Further to the detailed vector scanning mode, a raster scanned system and a combination of both techniques are under development.

The volumetric 3D laser display technology for true reproduction of spatial images can tremendously improve the viewers ability to interpret data and to reliably determine distance, shape and orientation. Possible applications for this development range from air traffic control, where moving blips of light represent individual aircrafts in a true to scale projected airspace of an airport, to various medical applications (e. g. electrocardiography, computer-tomography), to entertainment and education visualization as well as imaging in the field of engineering and Computer Aided Design (CAD).

Keywords: 3D display, volumetric display, autostereoscopic display, laser display, multiplanar display, three-dimensional imaging, spatial visualization, depth perception, air traffic control, man-machine-interface

1. INTRODUCTION

There has always been a desire in technology and science not only to recognize in a three-dimensional manner the interrelation of our three-dimensional world, but also to visually display it in natural geometry within the framework of today's man-machine-communication, in real time, interactively, and in color. The fast development of computer graphics has turned this desire into an expectation.

Often the phrase "three-dimensional display" is interpreted to mean a two-dimensional representation of a three-dimensional scene on a conventional display device that uses monocular depth cues like perspective, hidden contours or shades to give the observer an illusion of depth in the image. The spectator's spatial vision created by his interpretational ability and by his power of imagination of physical conditions.

This incompatibility between the current display systems and the real 3D world that is being simulated is most pronounced when the user must determine the spatial relationship of objects or otherwise use visual depth cues to interpret displayed information. Information displays are needed that better communicate the relative position of objects in space and provide complete visual cues. Imaging devices with the ability to display three-dimensional information in a realistic and natural manner can tremendously improve the viewers ability to interpret data and to reliably determine distance, shape and orientation.

An example for an application that would benefit greatly from a true 3D representation is air traffic control. Investigations at the Institute of Flight Guidance at the Technical University of Braunschweig, concerning safety in air traffic, have shown that man is involved in flying accidents at a proportion of more than 80 %. This mainly concerns crew, maintenace and air traffic control.[1] In order to increase flight safety it is advisable to improve relevant man-machine-interfaces in strict consideration of human factors. The design of displays is an essential part of the development process for man-machine systems. In the field of air traffic control spatial visualization techniques promise improvements regarding safety issues.

The problem is as old as air traffic control using radar displays: a three-dimensional space cannot be shown on a flat surface satisfactorily. The missing third dimension, in this case the flight altitude, must be indicated by figures. As a consequence a controller has to constantly observe all aircraft on the radar screen to form a mental image of the actual airspace situation. After an interruption, his mental image is disturbed and he needs some time for readjustment. In order to support controllers more effectively in judging the flight activities in the observed air space, innovative volumetric imaging techniques have to be provided. A true 3D volume display should be designed to complement state-of-the-art 2D radar displays for an improved performance needed on safety-critical observation tasks. This image generation technique ensures that many depth cues are satisfied automatically without the need for special glasses to be worn by the observer.

First this paper will discuss the physiological background of human depth perception in order to determine the necessary performance requirements, an operational 3D display device would have to meet. After a brief overview and classification of possible 3D display techniques follows the description of FELIX, an implemented volumetric display which was initially developed at the Youth Research Center in Stade in 1983 and then gradually improved in cooperation with the Institute of Flight Guidance.[2]

2. PHYSIOLOGICAL BACKGROUND OF HUMAN DEPTH PERCEPTION

Since the use of visual displays depends upon the visual capabilities of people, first the process of seeing and certain types of visual skills will be discussed. For optimal display design these factors have to be considered thoroughly.
Although the retina of a human eye represents a "2D receiver" we are able to perceive spatial depth. The main reasons for this remarkable talent will be briefly illustrated in the following sections.

2.1 Perceptual characteristics of vision

The human visual information processing to judge distance or depth is only partly determined by sensory characteristics of the eyes. An important role plays the information processing in mind. Our brain makes unconscious use of various strategies. The spectator's spatial vision is created by his interpretational ability and by his power of imagination of physical conditions. Most important in this context are the knowledge of physical laws and experiences from everyday observations. Examples for this kind of depth cues are:

- laws of perspective
- familiarity with size and shape of everyday objects
- familiarity with surface structures and textures
- obscurations and hidden contours
- light and shaddow effects

Distant objects take up a smaller angle than they do when close up. Textures change with distance and with viewing angle. Lines converge in the distance. Through experience we learn to interpret or translate these visual cues into distance or depth. With taking advantage of these empirical values it is possible to simulate depth in 2D representations. Already Renaissance artists have been very skilled in using shadows, relative size cues, texture gradients, perspective cues, and occlusion to generate a perfect illusion of spatial depth in their paintings.[3,4,5]

Assuming that humans normally live and move about in a three-dimensional world, it makes sense that the visual apparatus has evolved to piece together a three-dimensional reperesentation of the images that it sees. Despite this impressive mental capability for human vision one can't always rely on one's visual perception. Figure 1 may illustrate how easy it is to mislead or confuse our visual system. On the left side there are some bits and pieces of a picture. They look like corners and sides of some three-dimensional object. After putting them all together, the pieces do not quite fit.

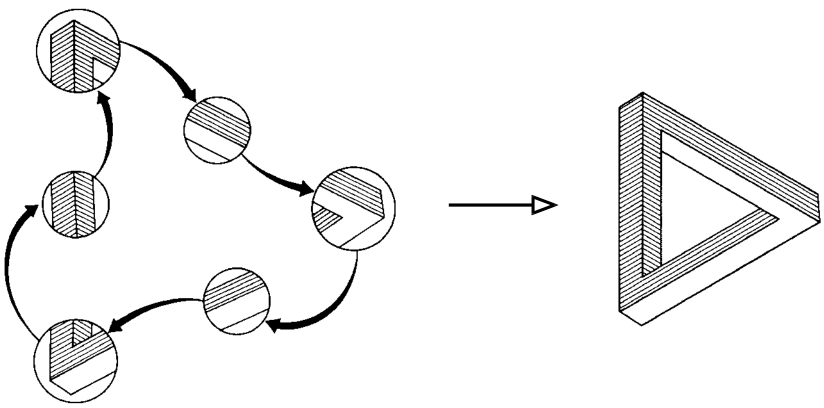

Figure 1: Optical illusion [5]

The figure is physically impossible. But there is nothing inherently impossible about the collection of lines and angles that make up the drawing. The individual features conflict with the global interpretation.[5] This example shows that for a true and realistic three-dimensional visualization additional depth cues have to be satisfied. The most relevant optical methods for this purpose will be explained in the following section.

2.2 Sensory characteristics of the eyes

Apart from the above mentioned perceptual characteristics of vision, visual performance is determined by sensory characteristics and optical methods of the eyes. A scheme of the eye's anatomy is given in Figure 2, showing the retina, the lens,and the cornea as main components.

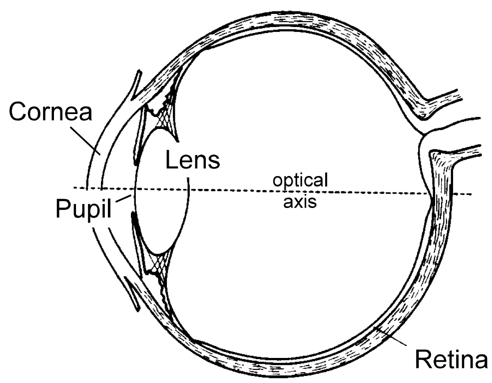

Figure 2: Anatomy of the eye

The cornea and lens refract the light rays entering the eye to provide a focused image on the retina. The focal distance adjustment, called accomodation is possible, because the lens is flexible and can change its thickness. The retina is a thin layer inside the eye which contains special light sensitive receptors that convert light images into physiological responses.[6]

The images in both eyes lie on the curved surfaces of the retinas, but it is not misleading to call them two-dimensional. A remarkable thing about the visual system is its ability to synthesize the two somewhat different images into a single perception of solid objects lying in three-dimensional space.

Figure 3 shows how the eyes pivot inwards for viewing near objects. This effect is called convergence. As the visual attention is directed to a particular object, it is necessary that the two eyes converge on the object so that the images of the object on the two retinas are in corresponding positions; in this way we get an impression of a single object. The two images are said to be fused if they do so correspond. The angle of convergence α and the degree of accomodation are signalled to the brain as information of distance.[7]

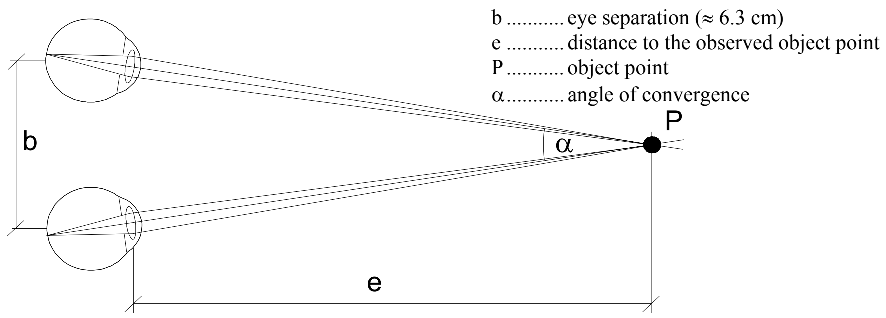

Figure 3: Accomodation and convergence[7]

Another depth cue is due to eye separation. The eyes are horizontally separated by about 6.3 cm and so receive somewhat different views from slightly different angles. This can be seen quite clearly if first one eye then the other is held open. Any near object will appear to shift sideways in relation to more distant objects, and to rotate when each eye receives its view. This slight difference between the images is known as parallax or binocular parallax. It gives perception of depth by stereoscopic vision (Figure 4).[5,7]

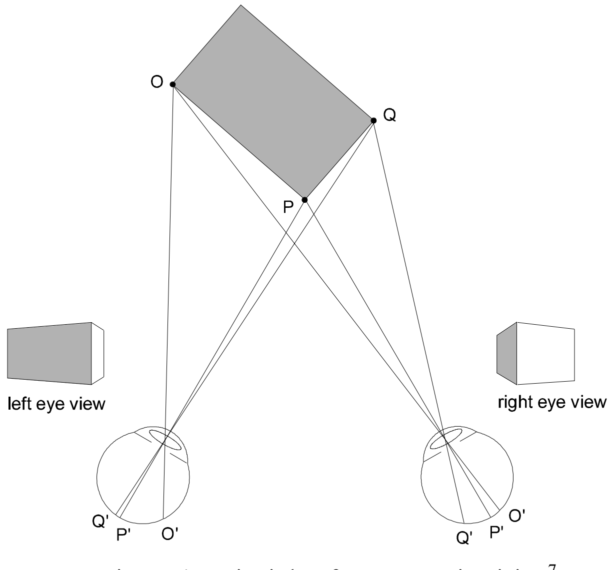

Figure 4: Principle of stereoscopic vision[7]

Besides the described binocular parallax the monocular or motion parallax is an important depth cue. This effect appears by changing the point of view or by moving the object. In both cases it leads to different views of the object. In contrast to binocular parallax the motion parallax can be perceived by people who aren't able to see steroscopicly such as one-eyed persons or persons who have one dominant eye.

3. 3D DISPLAY IMPLEMENTATION CONCEPT

Summarized the following methods have to be supported by spatial visualization techniques that are supposed to generate 3D information in a realistic and natural manner:[2,4]

mental image processing and a priori knowledge:

- laws of perspective
- known size and shape of everyday objects
- known surface structures and textures
- obscuration and hidden contours
- light and shaddow effects

optical methods:

- accomodation
- convergence
- parallax
- motion parallax

3.1 Overview and classification of 3D displays

The task of satisfying most important depth cues simultaneously proved hard to be accomplished. Until today there is no technical solution available that would fulfill all of the above mentioned requirements. There rather exists a variety of different approaches to three-dimensional imaging where each system has its characteristic advantages or drawbacks. True 3D imaging has advanced to include a broad range of complementary technologies. A detailed description of each is beyond the scope of this paper. However, the major categories are:

- stereoscopy (separate image generation for left and right eye)
- holography (wavefront reconstruction)
- multiplanar displays (spatial visualization in a volumetric display device)

Another criterion for characterization of 3D imaging is the distinction of stereoscopic methods which require visual aids like special viewing glasses (i.e. virtual reality) and so-called autosteroscopic techniques (i.e. holography or multiplanar displays) that avoid 3D glasses or similar head gear.

The search for a device able to enhance the realism of photographic images by reproducing a depth sensation was initially pioneered in the 1830s by Charles Wheatstone, who successfully developed the stereoscope.[8] In this technique, a stereo-pair is observed with special 3D glasses or the viewing field for each of the pairs is restricted by optical elements like lenticular sheets, parallax barriers or time sequential slits. The recent advances in stereo-pair displays have made them a suitable alternative for many applications. However, this display technology is not appropriate for multiple-person tasks or off angle viewing since it provides a virtual rather than a real 3D image. An actual example of state-of-the-art stereoscopic technique is virtual reality which has proven useful in several applications such as simulation and construction. A major disadvantage of this system may be the separation of the user from his environment and colleagues by the required headmounted display.

A fundamental problem of every stereo-pair display technology is its inherent unnatural depth perception. While accomodation will be kept on a constant level, depending on the distance between eye and display, only convergence of the eyes may vary according perceived depth. Usually both effects are closely related to each other when watching a natural scene. This unnatural perception may lead to visual fatigue, headache or uncomfortable feeling at the observer.

The second group of spatial visualization concerns holography where replication of the actual wavefronts is the ultimate goal. To date, animated, real-time, color holograms have been generated using a supercomputer at Massachusetts Institute of Technology (MIT). Up to now image resolution is low and image size as well as viewing angle is restricted to a small value. The information content of a typical hologram is several orders of magnitude larger than that of other 3D images. Progress toward real-time holography with higher resolution is handicapped by the limited information bandwith available in present-day electronic, computing, and communication systems.[10]

The third category of multiplanar or volumetric displays aims at the ideal three-dimensional image representation in a display volume with all-round view capabilities. Special viewing glasses are not required to achieve the 3D effect, so that volumetric systems are therefore by definition autostereoscopic. Various methods are known to achieve the goal of creating a 3D image by illuminating actual light sources within a described volume. They may be grouped into the three following categories:

- unrestricted, parallel addressability of the display volume
- oscillating mirrors
- moving screen / swept volume display

A first step to the ideal, inertial free, in three physical dimensions addressable projection display was performed by the two-step excitation of fluorescence. Intersection of two deflectable nonvisible radiation sources (i.e. IR-laser) excites visible fluorescence within a display volume of an appropriate medium. Figures are then created in space by repetitively scanning the point of intersection through the desired pattern in complete functional analogy to the method of forming 2D patterns on a cathode ray tube (CRT). Investigations have been carried out using mercury vapour and iodine monochloride gas, and also with a transparent crystalline display medium.[8] Unfortunately major physical and technological constraints could not be overcome yet. Before introducing an operational system based on this principle further research work has to be carried out.

In the category of oscillating mirrors either linearly moving mirror systems or vibrating varifocal mirrors are used to reflect a series of CRT images. The latter is based on a mirror constructed from a flexible membrane attached to the front of a conventional loudspeaker reflecting the image of a stroke CRT. The focal length of the mirror varies as low frequency signals are applied to the loudspeaker, thus enabling a large virtual image depth to be achieved by a small amplitude of vibration. This type of display is not truly volumetric because it only presents virtual images. Moreover the system is bulky and the field of view is restricted by the setup.[12,13]

Many attempts to develop multiplanar displays are based on moving target screens that sweep through a certain volume. This theory utilizes the phenomenon of visual persistance. The speed of motion of the screen is such that it cannot be perceived by an observer and the period of movement is, in general, higher than the flicker fusion frequency of approximately 15 Hz. A group of scientists from the University of Canterbury in Christchurch, New Zealand, proposed spinning a phosphored disk within the evacuated cylinder of a cathode ray tube, known as the Cathode Ray Sphere (CRS). The 3D images are created by controlling the gating and deflection of an electron beam so that the screen is addressed as it passes through the desired location. Images are currently displayed as a sequence of radial slices or sectors. High demands are placed upon maintaining the vacuum in the CRS with moving parts inside.[8,9]

Other rotating projection surface approaches avoid the problems with a vacuum tube. In the beginning of the 1980s Professor Hartwig of the University of Stuttgart lead the development of scanning systems that employ a precisely positioned laser beam scanning across a rotating, helical, translucent projection screen.[14] Since 1983 a group of the Youth Research Center in Stade worked on a similar project. Later on Texas Instruments, Kodak and the Naval Research Center followed with their investigations of multiplanar displays likewise based on the use of a rotating helical shaped projection surface.[12,13]

Main advantage of this approach is the comparatively simple display setup. A drawback is that the number of resolvable spots or vectors in the displayed image is limited by the modulation frequency of the beam and the positioning system. Usually the projecting laser beam will be deflected by mechanical scanners. Due to their inherent inertia their scanning frequency bandwith is restricted. Through the availability of novel micromechanical components, inertial-free acousto-optical deflectors and high performance laser TV projection systems new possiblities evolve to significantly increase the displayed three-dimensional resolution.

3.2 Display system design

The prototype system introduced in this section is based on investigations at the Youth Research Center and the Institute of Flight Guidance since 1983. Due to the simple system design the principle of a moving target screen that sweeps the display volume was chosen for implementation of a functional demonstration unit.

As illustrated in Figure 5, a semitransparent helical screen represents the core element of our multiplanar 3D display, called FELIX (this name is derived from a play on words with the word "helix"). It is made of glass fiber and mounted on a motor shaft. The helix is pivoted in a transparent acrylic housing. For synchronization purposes the driving motor is provided with a position encoder. In order to avoid vibration and excessive centrifugal forces that could damage the display the screen has to be balanced very carefully. In full operation it rotates at 1,200 RPM creating a cylindrical display volume of 250 mm height and 600 mm in diameter. This rotational speed leads to an image refresh rate of 20 Hz. Under dimmed ambient light conditions flicker is almost eliminated.

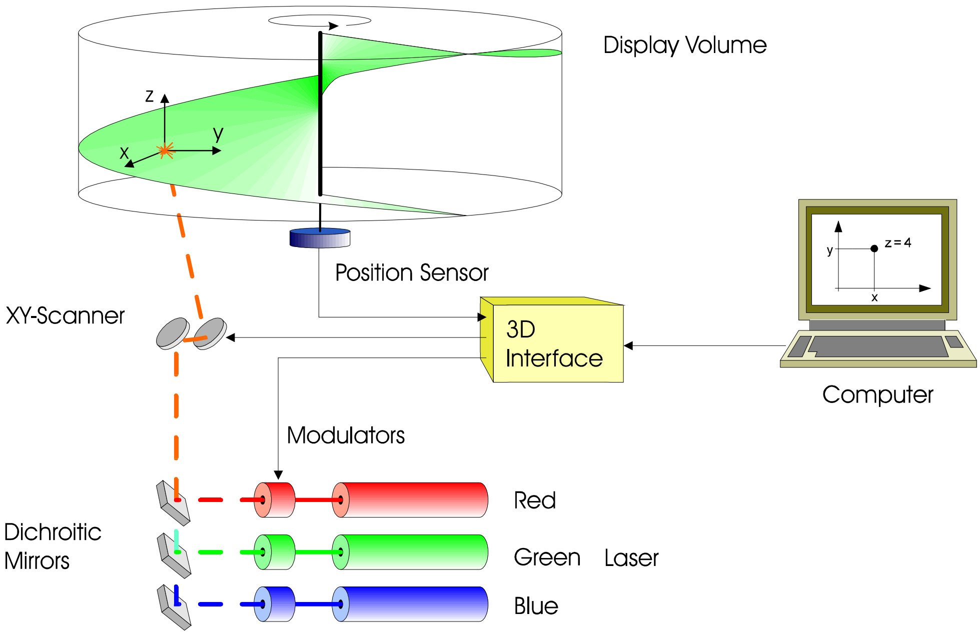

Figure 5: Principle of operation

Underneath the transparent enclosure an optical bench and an electronic interface are arranged. For the image generation a laser projection system is used. It consists of a laser beam, an electro-optical modulation unit and and a two-dimensional XY-scanner. The beam is scanned in X and Y direction. Through intensity modulation synchronized with the rotating screen the third dimension Z will be controlled. Computer controlled deflection and modulation of the laser beam allows all X, Y, Z points within the display to be addressed. The image can be in color using a combination of red, green and blue (RGB) lasers. As depicted in Figure 5, all three beams will be combined to one by optical means. Through separate modulation of each component any color can be mixed.

The optical property of the helical screen was chosen translucent, so that an impinging laser beam on the surface will be partly transmitted and partly reflected. This is important for the all-round view capability of the 3D display.

The following different scanning techniques have been investigated:

- 3D vector graphic
- 3D raster graphic
- 3D cursor

First a vector scanning mode was implemented. Two closed loop galvanometric scanners in orthogonal arrangement allow vectorized control in X and Y. Each scanner is driven by a digital to analog converter. Scanner control and spatial image generation is performed by a specially developed software written in turbo pascal. As a result wireframe graphics are presented within the display volume which a group of people can walk around and examine from nearly any orientation simultaneously without any visual aids.

Further to the detailed vector scanning mode, a raster scanned system is under development (Figure 6). Goal of this method is the generation of a spatial matrix of image points. In this way rastered three-dimensional images are created, complementary to the usual flat raster images on common TV sets or computer monitors.[15]

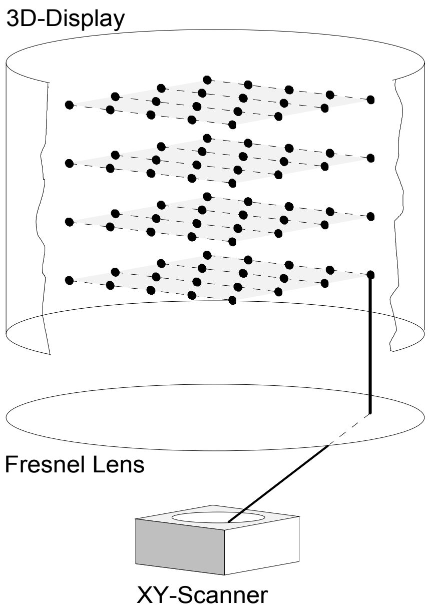

Figure 6: Principle of a raster scanned mode[15]

This technique was realized using high speed polygonscanners. As a result a cubical raster of 20 stacked image planes occured, each plane is composed of 20 lines; again each line was split in *vo*lume pi*xel* (called "voxel") through intensity modulation of the laser beam.

A third unit that was implemented in the demonstration display is called a "3D cursor". By variation of the phase difference between modulation frequency of the laser beam and rotational frequency of the helix the Z-dimension can be selected and marked by a light spot. Combined with a raster movement of this spot in X and Y direction a colored pointer can be positioned in the whole described volume. The horizontal movement is performed by tilting a mirror in two orthogonal axis which is controlled by a joystick. Color of the 3D cursor depends on the selected laser.

4. CONCLUSIONS

Since the 1940s many attempts to develop a volume display have been carried out. At that time the experimental approaches failed to come to a satisfactory operational stage due to technological restrictions. The demonstration system described in this paper refers to some of the proposed volumetric techniques extended by new ideas and state-of-the-art technology.

A multiplanar 3D image presentation approach in a space filling, volumetric display is suggested. Net result is the optical equivalent of a three-dimensional array of image points illuminated to form a model of the object which occupies a physical space with height, width and depth. Thus important depth cues for spatial vision like binocular and head-motion parallax are satisfied automatically without the need for special glasses to be worn. The observer’s interocular spacing provides the perspective difference which generates the binocular depth clues just like watching a natural scene.

The volumetric 3D display technology promises new possibilities in all areas where today perspective portrayal on flat screens or other pseudo 3D representations to judge physical conditions or motions still have to be used. Techniques enabling true reproduction of spatial images can tremendously improve the viewers ability to interpret data and to reliably determine distance, shape and orientation. Volumetric image production is of particular interest to the research being undertaken by the Institute of Flight Guidance at the Technical University of Braunschweig in the field of air traffic control. Moving blips of light could represent individual aircraft in a true to scale projected airspace of an airport. A true 3D volume display should perfectly complement state-of-the-art 2D radar displays for an improved performance needed on safety-critical observation tasks.

Other possible applications for this development range from medical uses in electrocardiography or computer-tomography, to entertainment visualization as well as imaging in the field of engineering and Computer Aided Design (CAD).

Results achieved with the simple demonstration setup have proved the feasibility of the chosen 3D display concept. The immediate goal of the continuing development is to transfer the existing system in practical steps of improvement. Through the availability of novel micromechanical components, inertial-free acousto-optical deflectors and state-of-the-art laser TV projection systems new possiblities evolve to significantly increase the performance of the suggested 3D display configuration.

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