New portable FELIX 3D display

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ABSTRACT

An improved generation of our "FELIX 3D Display" is presented. This system is compact, light, modular and easy to transport. The created volumetric images consist of many voxels (*vo*lume pi*xel*), which are generated in a half-sphere display volume. In that way a spatial object can be displayed occupying a physical space with height, width and depth.

The new FELIX generation uses a screen rotating with 20 revolutions per second. This target screen is mounted by an easy to change mechanism making it possible to use appropriate screens for the specific purpose of the display. An acousto-optic deflection unit with an integrated small diode pumped laser draws the images on the spinning screen. Images can consist of up to 10,000 voxels at a refresh rate of 20 Hz.

Currently two different hardware systems are investigated. The first one is based on a standard PCMCIA digital/analog converter card as an interface and is controlled by a notebook. The developed software is provided with a graphical user interface enabling several animation features. The second, new prototype is designed to display images created by standard CAD applications. It includes the development of a new high speed hardware interface suitable for state-of-the-art fast and high resolution scanning devices, which require high data rates.

A true 3D volume display as described will complement the broad range of 3D visualization tools, such as volume rendering packages, stereoscopic and virtual reality techniques, which have become widely available in recent years. Potential applications for the FELIX 3D Display include imaging in the fields of air traffic control, medical imaging, computer aided design, science as well as entertainment.

Keywords: 3D display, volumetric display, autostereoscopic display, laser projection display, three-dimensional imaging, voxel, FELIX, air traffic control, CAD

1. INTRODUCTION

For many years there have been several attempts to build devices which display in three dimensions. The work described within the scope of this paper is one of these efforts. Information display systems should be customized to provide the visualization needed to find the solution to a particular problem. Future display systems should therefore make use of state-of-the-art display technology to provide critical information in a natural and usable format to the viewers.

Perspective presentation of 3D images can be created by 3D software tools on a conventional 2D screen. The spatial impression depends on the spectator's spatial vision created by his interpretational ability and by his power of imagination of physical conditions. For a variety of disciplines ranging from architecture to computer aided design (CAD) and entertainment these tools often make use of computational rendering and visualization on high resolution cathode ray tubes (CRT) with impressive results. However, there are still many cases where rendered or perspective images cannot convey the depth information clearly without confusion. For example, many users of 3D CAD tools have problems with the correct positioning of objects in a perspective environment. In order to do this correctly designers rely on numbers rather than vision to position objects one coordinate by another. By using a three-dimensional display this problem could be overcome.

In the field of air traffic control spatial visualization techniques promise improvements regarding safety issues. The

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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 alphanumerically 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 air space 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 today's 2D radar displays for an improved performance needed on safety-critical observation tasks.

The 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. For those applications 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.

The following discussions will give an overview of former and existing volumetric 3D display technologies up to date followed by an introduction into the system architecture of the new portable FELIX 3D Display. The presented work is a joint project between the Vincent-Lübeck-High School in Stade, where related initial investigations have been started in 1983, and the Institute of Flight Guidance and Control at the Technical University of Braunschweig, Germany.

2. BASIC CONCEPTS AND OVERVIEW OF VOLUMETRIC 3D TECHNOLOGIES

The need for better displays of three-dimensional spatial and non-spatial information supplied by data gathering systems has long been recognized. A number of attempts to meet it have been made in several past and current development efforts. The general types of volumetric 3D displays - swept volume and static volume techniques - are quite different in concept and design. Figure 4 gives an overview of the basic classes with examples, which do not claim to be complete. Some approaches of related developments will be described in the following paragraphs.

2.1 Swept volume techniques

Several autostereoscopic volumetric display methods are under investigation in which a periodically time-varying two-dimensional (2D) image is used to sweep out a volume of space cyclically at a frequency higher than the eye can resolve. A spatial image is formed through persistence of vision, which exhibits several of the usual cues of daily depth perception, especially the compelling ones of stereoopsis and parallax.

The primary 2D pattern may be generated on either an emissive panel or a passive projection screen. The depth effect is achieved when the screen, which can take various shapes, is oscillated perpendicularly to itself, or when it is rotated, in synchronism with the cyclic 2D pattern. Alternatively, the screen may be fixed but may be viewed in an oscillating plane mirror so that its image is seen to oscillate. In any case, the screen (or its image) serves as a plane with which a volume is scanned in order to provide a three-dimensional blackboard or raster upon which various spatial patterns may be written.

2.1.1 Rotating screen

One of the early approaches, presented by the ITT Laboratories in 1960, consists of an especially programmed high brightness cathode ray tube (CRT) whose blips are optically transferred to a translucent rotating screen within a glass cylinder (Figure 1). The motor-driven panel turns at approximately 20 revolutions per second. To balance centrifugal forces on the screen, a black vane of equal size is attached on the opposite side of its motor drive shaft. [1]

In another arrangement, patented by R. Ketchpel in 1964, a phosphor-coated screen rotates in a vacuum, with a controlled electron beam striking its surface (Figure 2). 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 CRT with moving parts inside. [2]
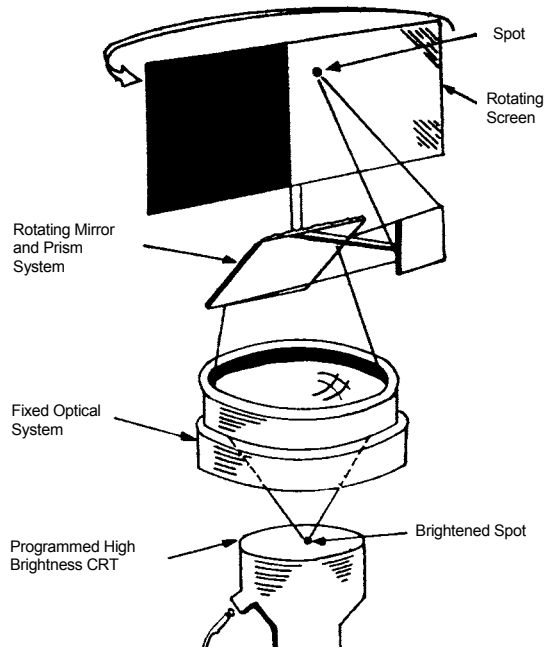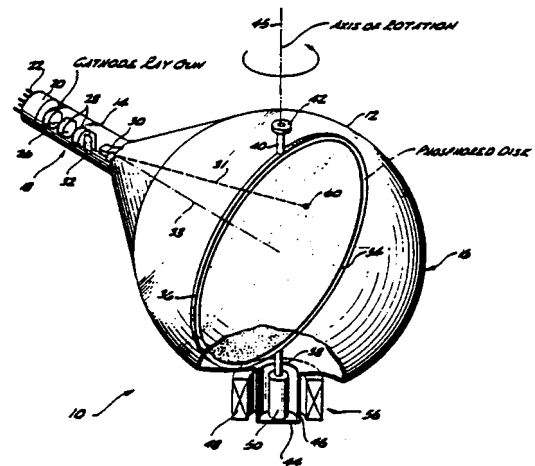
Figure 1: High brightness CRT projection [1]

Figure 2 : Rotating phosphor disk in CRT[5]

Based on this technology B. Blundell, A. Schwarz et. al. from the University of Canterbury (Christchurch/New Zealand) presented a volumetric display, called "Cathode Ray Sphere CRS", in 1992. The screen rotates at a frequency of approximately 15 Hz and images are refreshed during each rotation. The screen is coated with phosphor, which provides a high conversion efficiency and short persistence. A rapid decay in phosphorescence is essential to avoid "trails" caused by the screen moving a discernible distance while still emitting light of visible intensity. The dead zone problem has been overcome in this prototype by the use of two or three electron guns, arranged in such a way as to permit each to write to the screen when it is lying within a defined region. The positioning of the guns ensures that their respective dead zones do not coincide. The ability to depict color images on the CRS is achieved by coating both sides of the screen with different color phosphors, so that each colored portion sweeps out the entire display volume in a complete revolution. [3]

In the early 60s, R. J. Schipper described an emissive, X-Y addressable, thin-film electroluminiscent panel rotating within a transparent plastic ball. At the time, high speed light emitters were extremely costly or cumbersome seriously hindering the development of large prototype systems. With arising new technologies in the late 70s some of the constraining engineering problems could be overcome. Figure 3 shows a volume display system developed by E. Berlin at MIT. He proposed using a 2D matrix of light emitting diodes (LEDs) with the display electronics residing on the rotating matrix. For high-speed data communication an axially placed infrared serial data link was installed. The display resolution is a function of the number and density of LEDs, the speed of rotation, and the rate at which the LEDs can be pulsed. [4,5,6]

The above described display systems are characterized by rotating flat surfaces. Another group in this field uses rotating curved screens. These configurations simplify part of the optical design.
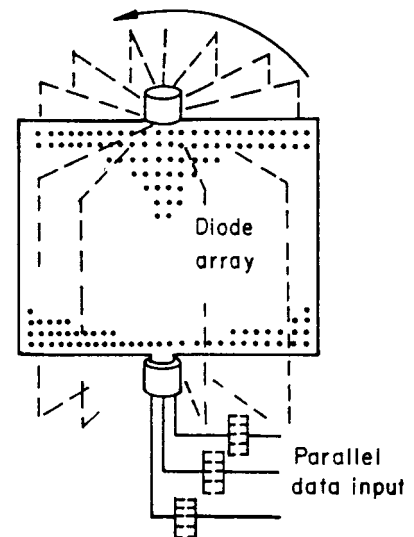

Figure 3: Rotating LED array [24]

VOLUMETRIC 3D DISPLAYS

Swept Volume Techniques

Static Volume Techniques

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rotating screen

flat surface

- high brightness CRT projection (Parker/ Wallis, 1948; ITT Lab. 1960)
- electroluminiscent panel (R. J. Schipper et.al., 1963)
- Cathode Ray Tube Imager (R. D. Ketchpel, 1964)
- LED array (E. Berlin, 1979)
- Cathode Ray Sphere (B. G. Blundell et. al., 1992)
- laser projection (R. Batchko, 1992)
- 3D Rotatron (S. Shimada, 1993)
- rotating reflector (C. Tsao, 1995)
- projection with laser diode array (G. Favalora 1996)

curved surface

- Spherical Spiral Display (D.W. Perkins, 1962)
- helical surface: W.D.Chase, 1976;
  R. Hartwig, 1976;
  "FELIX 3D-Display", 1983;
  R.D. Williams, 1988 "OmniView";
  R. Morton, 1990;
  P. Soltan, 1992
- Archimedes' Spiral (H. Yamada, 1986)

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oscillating screen

- vibrating CRT (~ 1940)
- phosphor screen in CRT (E. Withey, 1958)
- moving mirror (~ 1960)
- reciprocating screen (C. Tsao, 1995)

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varifocal technique

varifocal mirror

- oscillating mirror (A. Traub, 1967)
- oscillating mirror (E. Rawson, 1968)
- articulating mirrors (C. Anderson, 1968)
- oscillating mirror (L. Sher, 1976 "SpaceGraph")

rotating lens

- "XYZ Scope" (J. Fajans, 1979)

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two-step upconversion

solid

- fluorescence in $CaF_2:Er^{3+}$ with use of filtered xenon lamps as excitation sources (J. Lewis et.al., 1971)
- intersecting infrared laser beams in rare earth-doped heavy metal fluoride glass (E. Downing et.al., 1994)

gaseous

- intersecting laser beams in Rubidium vapor (E. Korevaar, 1989)

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miscellaneous

- stylus in gelatine material (Chrysler, 1960)
- 3D fiber optic display (A. Gery, 1983)
- voxel addressed by optical fiber (D. Macfarlane, 1994)
- field-sequential projection on stacked electrically switchable mirrors (T. Buzak, 1985)
- field-sequential projection on stacked polymer dispersed liquid crystal displays (E. Paek, 1996)

Figure 4: Overview of basic volumetric 3D display technologies

In the early 60s D. Perkins suggested a "Spherical Spiral Display" which is matched to radar-type 3D inputs. Like the sphere, the spherical spiral is the locus of circles with a common center and distributed about an axis that is the diameter of all the circles (Figure 5). In addition, each circle of the spherical spiral has a radius directly proportional to its angular position above the common axis. As the developed figure is rotated about its vertical axis at a constant velocity, the radius of the surface intersection with a plane containing the axis varies linearly with time. A small, high-intensity light source projects a collimated beam through a simple optical system onto manually controlled mirrors at the display center. The mirrors direct the beam to any azimuth and elevation. There is a fixed, mechanical shutter with three slits, so that three separate targets can be displayed on common azimuth and elevation angles. [7]
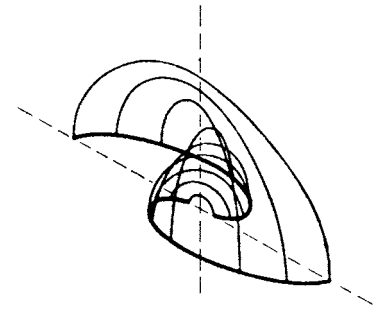
A 1976 patent issued to W. Chase uses a series of helically stepped pie-shaped glas sections where frames of strobed images are projected on.[8] While rotating, the projection plane moves stepwise in depth. For a continuous movement he suggested to employ a smooth helical screen (Figure 6).
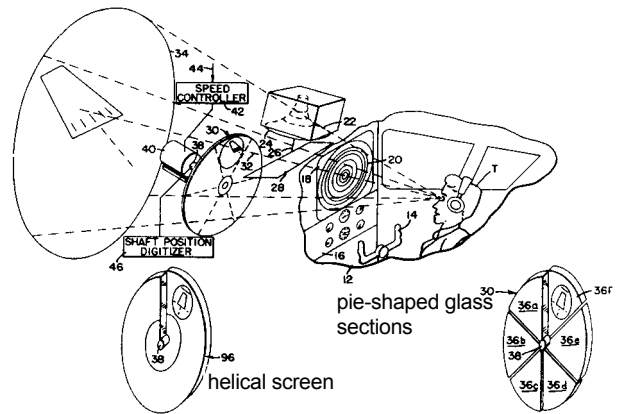
In 1982 Prof. R. Hartwig publicly presented a laser projection on a helical screen at the University of Heidelberg (Figure 7).[5,9,10] The rotating helix sweeps out a cylindrical envelope, providing a volumetric display medium through which scanned laser pulses are projected. The hitting laser beam will be scattered from the rotating surface causing a visible light spot. The spatial position of the emanating voxel within the display is determined by the momentary location of the laser beam's intersection with the rotating helix. Due to the comparatively simple system design this approach was used in different variations by other research teams.

In 1983 students a the Vincent-Lübeck-Highschool (Stade, Germany) started their investigations on helical screen volumetric imagers which laid the basis for the development of the "FELIX 3D Display" decribed in this paper. The work focuses mainly on different screen shapes, a modular and portable setup, advanced projection techniques and software development.[9,11,12]

In 1988 R. D. Williams and F. Garcia demonstrated a display wherein a scanned laser beam is displayed upon a continously rotating disc that is mounted on a motor shaft at an angle. Later they also employed a helical surface in their device further known as the "OmniView 3D Display".
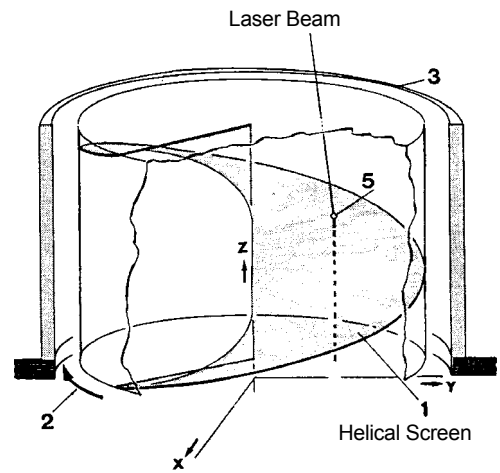
Another helix approach was suggested by R. Morton. Instead of a laser he used a CRT projector as the imaging source. The unique aspect of this patent is the use of an anamorphic lens to correct for the variations in the focal distance of the various points on the helical surface. This special correction lens rotates with the projection surface to form a clear projected CRT 2D image on the curved screen.

Since early 1990 a research team (P. Soltan, M. Lasher et. al.) at NRaD, the RDT&E Division of the Naval Command, Control and Ocean Surveillance Center (NCCOSC, San Diego), works on the development of laser-based volumetric 3D displays also based on a helical surface. Reflective and translucent screens have been investigated. One main research result was the development of a novel high performance acousto-optic scanning system leading to higher image resolutions. This was achieved in cooperation with NEOS Technologies who also work on a similar 3D display device. [13]

Figure 5: Spherical Spiral Display [7]

Figure 6: Strobed images projected on a rotating helical screen [8]

Figure 7: Laser projection on helical screen [10]

2.1.2 Oscillating screen

Another class of swept volume displays may be characterized by an oscillating screen that moves back and forth or up and down. An example from the 40s uses a vibrating CRT, where the images output to the screen are synchronized, within each oscillation cycle, to the position of the tube. Unfortunately, the high mass of the tube would make it difficult to obtain the desirable rapid acceleration and deceleration at each end of its travel. [14]

A more practical attempt suggested by E. Withey later in 1958 moved the phosphorous screen within the CRT rather than the whole CRT itself (Figure 8). The cathode ray screen is mounted within a vacuum tube behind a transparent viewing globe. The screen is driven in oscillation, piston-like, toward and away from the observer along the Z-axis while an electron gun illuminates it from the rear. [15]
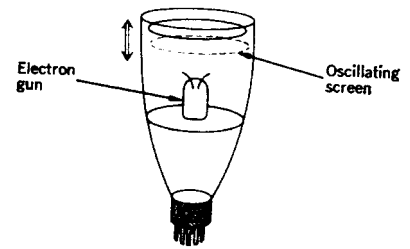
In a variation of the oscillating-screen method, a CRT image is viewed from an oscillating plane mirror. The mirror moves in such a way that the visual path length is swept periodically and the CRT image apparently sweeps out a volume. The principal drawback of this scheme is its limited viewing angle, which is determined by the display volume and the reflective surface coverage. [7]

Figure 8: Oscillating phosphor screen in CRT [17]

Recently C. Tsao described a reciprocating approach, where an optical-mechanical mechanism consisting of a screen and a converging lens is moving back and forth. A LED projector and a slide projector with a high speed LCD shutter were used as the image source. [16]

Due to the oscillating movement and the arising inertial forces all displays of this category have mechanical problems with vibration and noise. The mechanics of the system limit the oscillation amplitude, and hence the depth of the three-dimensional image swept out by the screen. Because of the accelerations they involve, the oscillation frequency is limited causing considerable flicker of the displayed images. Also the design problems of maintaining constant image size and focus and of balancing air pressures (unless an evacuated volume is used) make them a difficult proposition.

2.1.3 Varifocal technique

The varifocal techniques are not strictly volumetric as they produce virtual images. The changing focal length gives rise to a virtual image field depth far greater than the physical amplitude of the membrane oscillation or lens rotation. Nevertheless they are considered in this chapter as they share common characteristics with other swept volume techniques.

In 1961 it was noted that a thin sheet of aluminized plastic film stretched taut over an airtight circular frame could be pneumatically distorted to form a good quality concave or convex mirror, and that the curvature, and hence the focal length, of the mirror could be conveniently varied by decreasing or increasing the static air pressure on the film's back surface. A few years later, A. Traub recognized the potentialities of the varifocal mirror for autostereoscopic imaging.

The essentials of the method are illustrated in Figure 9. The thin aluminized mirror film is driven sinusoidally from a loudspeaker. If the mirror film is taut enough and the amplitude of the oscillation not too large, the mirror's surface is essentially a sphere of continuously changing curvature. Thus, when an observer views an object (such as the face of a CRT) by reflection in the mirror, the changes in curvature cause a corresponding change in the position of the reflected image. The result is an autostereoscopic image that is essentially a transparent stack of two-dimensional images viewed in the varifocal mirror. [17]
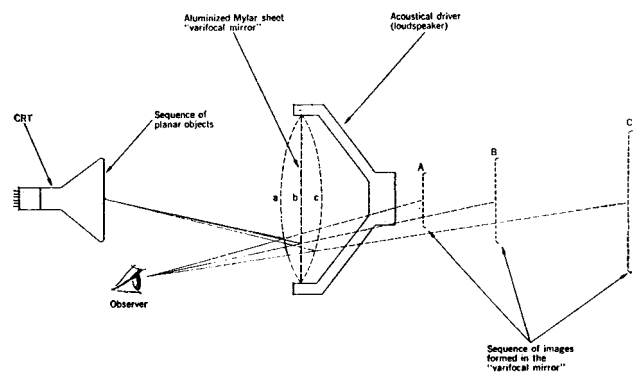
In 1976 L. D. Sher built the first general-purpose, computer-driven display of this type, later known as the "SpaceGraph 3D Display". [8]

Figure 9: Varifocal mirror for 3D imaging [17]

Like in the oscillating mirror approach described in 2.1.3 a principal drawback of this scheme is its limited viewing angle, determined by the virtual display volume and the reflective surface coverage. It cannot provide an all-round view of the image.

Another varifocal approach, proposed by J. Fajans 1979, is known as the "XYZ Scope". It uses a lens rotating about its diameter instead of a vibrating mirror film. [18] The rotating lens is said to cause aberrations as the viewer moves out of the center axis of the lens.

2.2 Static volume techniques

Systems which are able to create a display volume without the need to employ mechanical motion are classified as static volume displays. The goal of this technique is to provide emissive voxels at a large number of locations in a static setup incorporating no oscillating or rotating parts. Several interesting attempts have been made using transparent crystals, gases, electronic field sequential techniques, and others. Some interesting approaches will be discussed in the following paragraphs.

2.2.1 Two-step upconversion

The direct excitation of a medium in space is a scheme long favored by researchers. As the "ultimate" 3D display, many foresee something like a plasma-filled medium that is excited within the display volume to produce a glow at a single point. The point would be controllable at velocities comparable to the spot velocities of a CRT.

The phenomenon of stepwise excitation of fluorescence seems to be one suitable approach for the generation of isolated fluorescent voxels. This physical effect has been known since the 1920s, when it was first observed in mercury vapor. The process occurs in the presence of radiation of two distinct frequencies, each of which is resonant with an electronic transition.

In 1971 J. D. Lewis et. al. of Batelle Laboratories described a 3D display concept based on the above mentioned process.[19] They succeeded in generating two faint spots of light inside a transparent crystal of erbium-doped calcium fluoride with the use of filtered xenon lamps as excitation sources (Figure 10). They proved the feasability of this concept and indicated that the shortcomings were primarily associated with the lack of suitable excitation sources and materials with sufficient infrared to visible conversion efficiency.
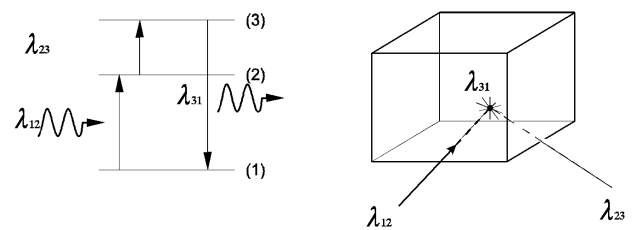

Figure 10: Two-step excitation of fluorescence [19]

Based on the pioneering work described above, E. Downing et. al. at Stanford University, presented in 1994 a three-color 3D display with improved upconversion materials using high power infrared laser diodes. The laser beams intersect inside a transparent volume of rare earth-doped heavy metal fluoride glass to address red, green, and blue voxels by sequential two-step resonant absorption. Three-dimensional images are drawn by scanning the point of intersection of the lasers around inside of the material.[20] The demonstrated proof-of-principle prototype has the size of a sugar-cube.

Another approach, patented by E. J. Korevaar in 1989, used a gaseous volume enclosed in a sealed glass container. For the demonstration, two diode lasers were intersected in Rubidium vapor. Rubidium was chosen because the required wavelength corresponded to currently available diode lasers.[21] This setup requires heating of the Rubidium within a vacuum chamber which makes it difficult to design a large scale display volume.

2.2.2 Miscellaneous

Apart from the described technologies several more interesting attempts have been made in the field of static volume displays. Early approaches from the beginning of the 1960s proposed the mechanical insertion, support, and translation of objects or particles in a volume. E. g. a stylus which can write in three colors was suspended in a tank of transparent gelatin. The servo-driven stylus moves through the gelatin, leaving a colored trace. This concept is limited to low data rates but provides history or track, since the unit itself handles integration and storage.[7] Actual stereo-lithography processes for rapid prototyping purposes may be seen as a modern application of this technology.

An alternative static volume procedure, suggested by D. Macfarlane in 1994, proposed to use a three-dimensional stack of volume elements, made of an UV-curved optical resin doped with an organic dye. Each voxel is addressed by an optical fiber that pipes light to the voxel.[22]

The last type of display mentioned in this paper makes use of a field sequential technique with no moving parts. The proposed field-sequential, discrete-depth plane, 3D display consists of a series of electrically switchable mirrors stacked one in front of the other. Each mirror can be switched into one of two states: reflecting or transmitting. When an image from a CRT is reflected from the stack of mirrors, the apparent distance of the image from the observer is a function of the position of the nearest reflecting mirror.[23] The result is a virtual three-dimensional image with similar restrictions as for the oscillating and varifocal mirror technique.

Also field-sequential projection on stacked polymer dispersed liquid displays is suggested (E. G. Paek, 1996). Each plane can be switched into a transmitting or a scattering state.

With the available present technology the three last mentioned techniques have performance and technical limits that may be addressed with future developments.

3. OPERATING PRINCIPLE

The new FELIX generation (Figure 11) is a compact, light and easy to transport system of modular design. It consists of the following main components:

- display volume containing the projection screen,
- projection units with integrated lasers,
- projection unit drivers and motor power supply,
- control PC with 3D interface.

The core element of the current prototype is a target screen of 30 cm in diameter, rotating with 20 revolutions per second. The screen is mounted by an easy to change mechanism making it possible to use appropriate screens for specific purposes of applications. Up to now two different types of screens have been tested: a double helix and a single turn helix. The light source is a small diode pumped Nd:Yag-Laser (532 nm). The implementation of a 635 nm laser diode is in preparation. A high speed acousto-optic scanner unit deflects the laser beam. This device is fast enough to produce images of up to 10,000 voxels with a flicker free image refresh rate of 20 Hz. Due to operational reasons the effective resolution is somewhat less. To create three-dimensional objects in the addressable volume of the display, the imaging components have to be synchronized. The main work is done by especially designed control software. It sorts the voxels of the three-dimensional image by their z-coordinate and calculates the actual rotation angle of the projection screen from the received position signal. Finally, the control software sends the x- and y-coordinates according to the actual screen position to a digital/analogue-converter-card. Thus, the system can be controlled by a standard PC-Notebook, because no special hardware is required. The developed control software has its own graphical user interface providing the user with several animation features such as rotation, translation, zoom etc. While operating, the CPU has to transfer data from the RAM to the projection unit continuously. Simultaneously, it synchronizes the data output with the position of the rotating projection screen. While the output process is active, the user cannot interact with the computer, for instance to modify the three-dimensional image.
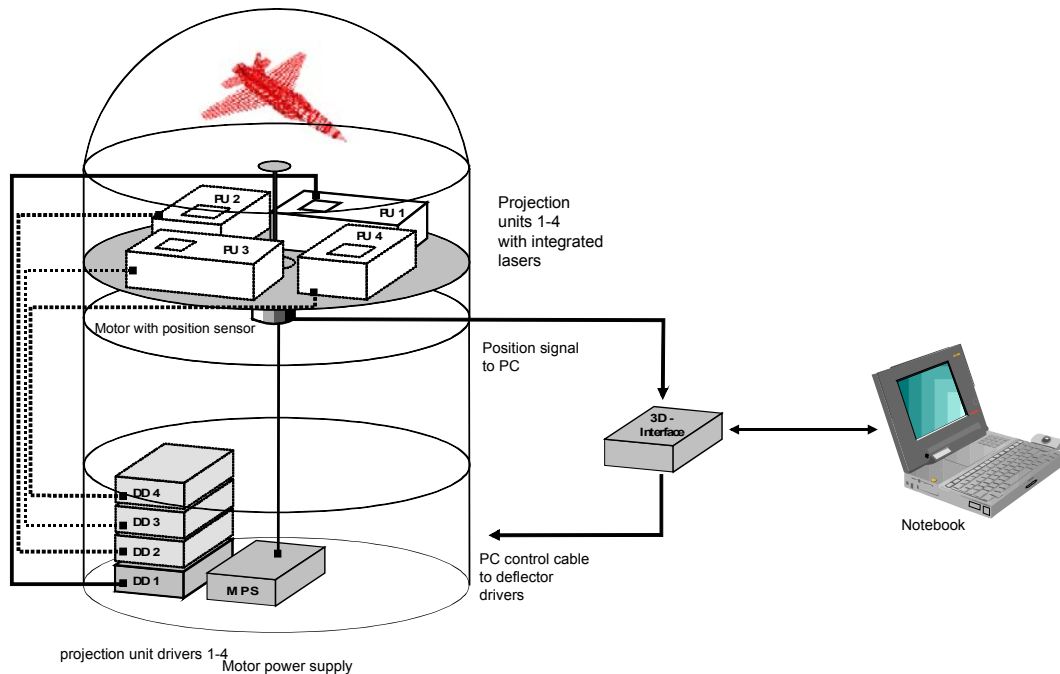

Figure 11: Modular FELIX system architecture

To allow background operation of the FELIX 3D Display a second generation of hardware interface had to be developed. This system had to be faster than the digital/analog-converter-card (DAC).

In the new hardware concept synchronization has been separated from the output process. A special PC card with an internal frame buffer is integrated in the PC and stores the image information. This hardware provides high data rates required by state-of-the-art fast and high resolution scanning devices. On board it has high speed DACs which are fast enough to control the 5µs acousto-optic deflection unit without any problems. In addition to the x- and y-coordinates it sends a 20 Hz clock signal to the display. Once the card is initialized no more CPU time is necessary to control the output process. A second interface card controls the motor speed to synchronize the projection screen's position with the clock signal. Applications running under Windows 95 can now simply write their three-dimensional data into the display RAM without influencing other processes. Software tools that convert standard 3D CAD formats to a FELIX displayable format are under development.

4. PROJECTION TECHNIQUES

Different methods of creating three-dimensional images haven been investigated with the FELIX 3D Display. The two conventional techniques also used in today's common displays are vector graphics, e.g. used for image representation in oscilloscopes and raster graphics, used with CRTs. A third technique referred to as *random access graphics* is also discussed in this section. Each of the mentioned three techniques can be realized by different projection units. Application characteristics of the three techniques, concerning the projection units investigated with the FELIX 3D Display are described.

4.1 Vector graphics

Employing vector graphics, spatial images are created which consist of lines instead of single voxels. Objects are drawn as a combination of daisy-chained lines onto the rotating projection screen. The third dimension of the generated line graphics is given by the continuous movement of the screen. The vertical line inclination increases with decreasing scanning speed. As a result, in this approach a horizontal cross section used by one displayed line cannot be used by any other simultaneously. With this technology low resolution vector graphics can be achieved.

4.2 Raster graphics

As a result of the investigation of raster graphics with the FELIX 3D Display it has turned out to be most comfortable to work with a fixed spatial raster. In this case the image volume is filled with a fixed number of voxels arranged in lines analog to the pixels of a TV picture. In the FELIX 3D Display forty equidistant lines form one plane. Forty of these planes are stacked to form a fixed three-dimensional array of voxels (Figure 12). The software has the task to select picture relevant voxels. Non relevant voxels are blanked by modulation of the laser beam.

One advantage of this raster technique is the quite simple image generation for the computer. It only has to modulate the laser beam in an adequate way. As the images are composed of transparent voxels, objects situated in the background are also visible. Therefore the illuminated voxels have to be chosen carefully, otherwise the displayed objects appear in a clutter. In contrast to the computer monitor where most of the screen area is used for information display, in a volumetric display only selected voxels are addressed.

The fact that also the non relevant voxels have to be scanned, regardless if they are used or not, is one disadvantage of the described raster technique. To avoid this disadvantage, the random access approach was investigated.
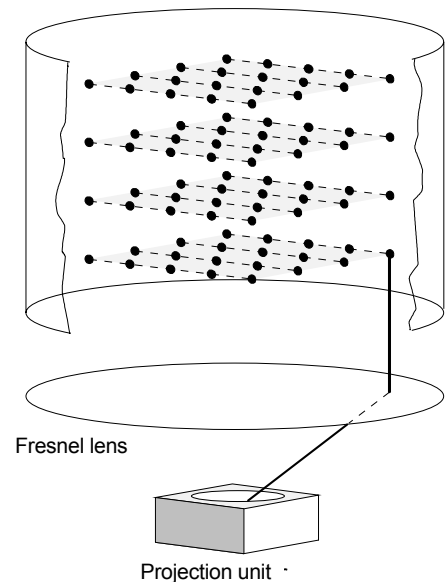

Fresnel lens

Projection unit ·

Figure 12: Fixed three-dimensional array of voxels

4.3 Random access graphics

Random access graphics are also based on a fixed array of voxels but only the relevant voxels have to be scanned. Non relevant voxels are not considered. This reduces the amount of storage capacity in comparison with the common raster technology. The majority of volumetric images displayed in laser-based swept volume displays require only a fraction of the addressable space. Therefore the random access graphics approach saves data resources and reduces the amount of data which must be transmitted to the projection unit.

The software sorts the voxels to be displayed by height. Each voxel is stored as a data set of its xy-position and the appropriate display time, determined by its z-coordinate. The data are read out sequentially to the projection unit, which directs the laser beam to the corresponding xy-position. Because of the free choice of the coordinates of the voxels it is possible to display relevant areas of the volumetric image with higher voxel density, which means in a more detailed way.

5. PROJECTION UNIT DESIGN

According to the above described projection techniques the following projection units have been investigated. The modular design of the new FELIX generation enables the user to operate with only one of these units or several of them in parallel. If required by the application a combination of different projection units is conceivable.

5.1 Galvanometric projection unit

Galvanometric scanners have long been used by science and industry in optical scanning. In the FELIX 3D Display galvanometric scanners may be implemented for vector graphics, because they can draw lines without any interruption. A small mirror (3 x 3 mm) oscillates around an axis to deflect a laser beam in one dimension continuously. A XY-scanning unit can be realized by arranging a second galvanometric scanner perpendicularly to the first one. The main disadvantage is the mechanical inertia limiting the number of lines that can be displayed to a few hundred. This would be enough for a two-dimensional image but is not sufficient to display more complex 3D objects. Despite the limited spectrum of objects, which can be displayed, the advantage of this technique is the quite easy realization of a multicolor display, by mixing modulated red, green and blue laser beams, which are turned on the scanning unit as a single beam. Using mechanical scanners in a 3D display with a rotating screen makes it also necessary to consider the time needed to move the laser beam from one position to the next one with respect to acceleration and deceleration processes.

5.2 Polygon projection unit

The projection unit based on a polygon scanning system makes it possible to display 3D images with the raster graphics technique. For our experiments we were provided with a prototype of a state-of-the-art laser television projection unit by C. Deter (Laser Display Technology, Gera, Germany, Figure 13).[25] To form a three-dimensional raster the projection unit has to draw planes consisting of lines. Therefore the applied raster scanning projection unit uses two different scanners: a high-speed polygon scanner operating at 32kHz to draw horizontal lines and a galvanometric scanner to deflect the beam orthogonal to these lines. The galvanometric scanner may work with lower frequencies. Both scanners have to be synchronized carefully by electronic means to provide a stable raster. In addition to the scanners an intensity modulator (e.g. electro-optical modulator) for the laser beam is needed to display only selected voxels in the volume. With red, green and blue lasers and three intensity modulators one can also create images of multicolor nature. The number of voxels per line scan is determined by the speed of the modulator. The control unit must only regulate the modulator to blank the beam at the right time. To create reasonable volumetric images the distances between two lines and two planes should be as small as possible. A high density three-dimensional raster requires faster scanning systems than the ones available today.
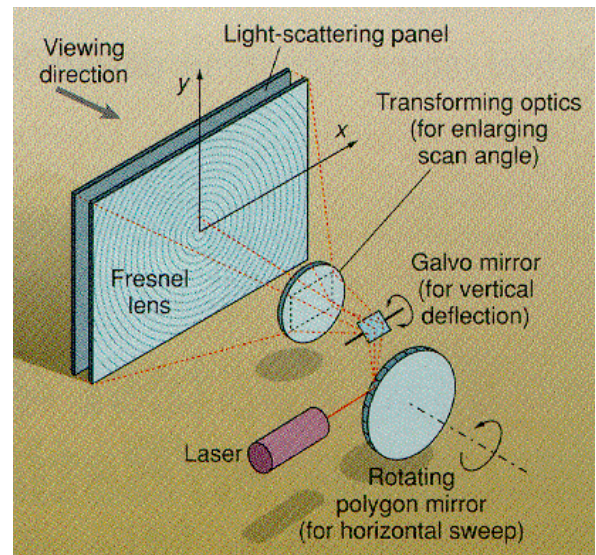

Figure 13: Principle of a laser TV projection unit using a polygon and a galvo scanner (by LDT)[25]

5.3 Acousto-optic projection unit

An acousto-optic XY-deflection unit is convenient to display images with the random access graphics technique. The AO-scanner integrated in the FELIX 3D Display contains TeO_2-crystals, which are passed by acoustic waves. The acoustic waves generate a refractive index wave that behaves like a sinusoidal grating. An incident laser beam passing through this grating will diffract the laser beam into several orders. The angular position of the first order beam is linearly proportional to the applied control voltage. The access time to turn the laser beam on a specific position is given by the transition time of the acoustic wave propagation across the optical beam. An acousto-optic projection unit is much faster than galvanometric scanners because it has no moving parts. The applied scanners used in the new portable FELIX 3D Display has an access time of 5μs leading to a resolution of up to 200,000 voxels per second.
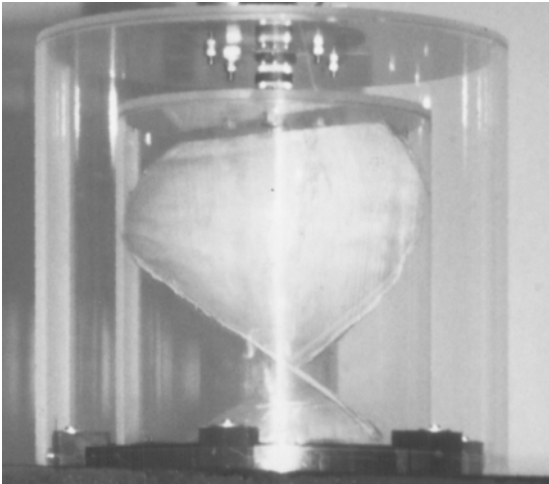
6. SCREEN DESIGN
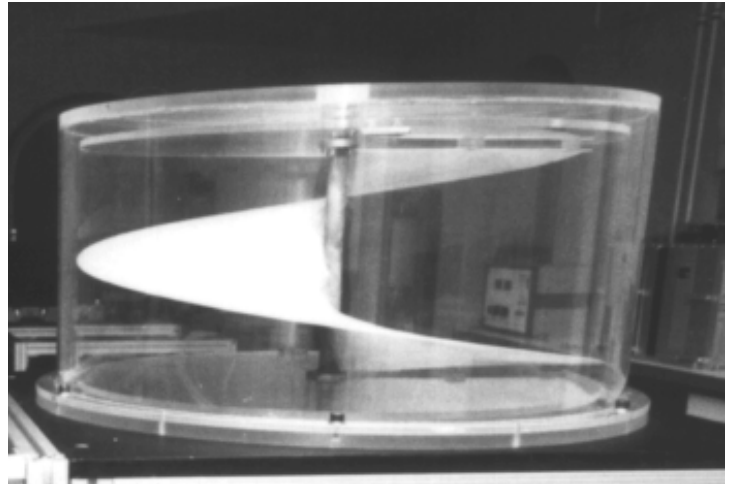

Figure 14: FELIX with a double helix (1985)

Figure 15: FELIX with a single turn helix (1992)

In the field of swept volumetric displays different approaches have been made. The new FELIX generation employs different kinds of rotating helical shaped screens. This technique facilitates a simple hardware configuration with an easier mechanical and optical construction than oscillating or rotating planar screens. The rotating screen operates at a constant rate. Also evacuation is unnecessary since the trapped air moves along with the screen. The two investigated helical shapes are a double turn helix (Figure 14) and a single turn helix (Figure 15). Disadvantages of this technique are the presence of occlusion zones, where vision is blocked, and dead zones that are not addressable by the imaging beam.

In the FELIX 3D Display the displayed image can be seen from almost any angle with a few occlusion zones. In these zones sections of the image are hidden from the viewer by parts of the rotating helix or the axis. Number and size of the occlusion zones depend on the surface's shape and are quite severe with the double helix system. Dead zones are not addressable regions of the swept volume.[26] One of these dead zones is a coaxial cylinder about the rotation axis. Other dead zones result from parts of the projection screen being between the projection unit and the target voxel position. By using a Fresnel lens this problem can be overcome. Another disadvantage of the double helix is the required precision in the manufacturing of the projection screen. As the image will be refreshed each half rotation cycle both screen halves have to coincide exactly. Slight asymmetries in the shape, lead to discontinuities in the generated image. With a rotation frequency of 10 Hz an image refresh rate of 20 Hz is achieved. In this case only half the motor speed is required. Though being a mechanical advantage at a first glance, the slow rotation of the screen disturbs the visual perception.

The usage of a single turn helix within the FELIX 3D Display can reduce the dead zones as well as the occlusion zones. Here an image refresh rate of 20 Hz corresponds to a rotation frequency of 20 Hz which improves the visual perception compared to the double helix.

7. CONCLUSIONS

A new modular and compact design of the FELIX 3D Display has been developed. It is based on a swept volume technique, generating an array of voxels within a half sphere. The modular approach enables flexible use of innovative hard- and software components. Different projection units may be mixed for the specific purpose of the application in order to improve the flexibility of the system.

The presented interface hardware provides high data rates required by state-of-the-art, fast, and high resolution scanning devices, which eases three-dimensional image computation and display. The implemented new software concept aims at representing standard 3D data formats (e.g. CAD formats) in the FELIX display.

One of the greatest advantages of volumetric displays like FELIX is the ability to present dynamic three-dimensional images which can be viewed by any number of viewers from almost any angle. Stereoscopic displays, however, like virtual reality systems, are limited to only one viewer at a time.

Through the availability of novel micromechanical components, inertial-free acousto-optic deflectors and state-of-the-art laser TV projection systems new possibilities evolve to significantly increase the performance of the suggested 3D display configuration.

A true 3D volume display as described will complement the broad range of 3D visualization tools, such as volume rendering packages, stereoscopic and virtual reality techniques, which have become widely available in recent years.

Possible applications for the FELIX 3D Display are disciplines in which the spatial visualization of data can simplify or accelerate the working process. Some examples are as follows:

- visualization of complex data structures,
- air traffic control,
- CAD/CAM (Figure 16),
- chemistry/physics (analysis of molecule structures, molecular reactions),
- medical imaging (electrocardiography, MRI)
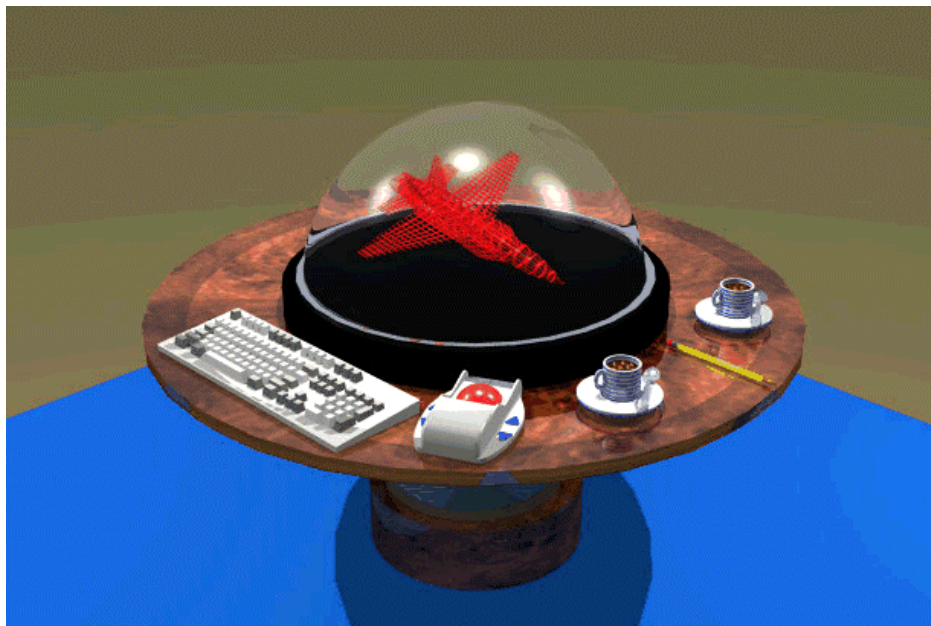- education, arts, entertainment, advertisement.

Figure 16: Design study of a future FELIX 3D-CAD-display

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