FELIX 3D Display: Human-Machine Interface for Interactive Real Three-Dimensional Imaging

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Abstract. Flat 2D screens cannot display complex 3D structures without the usage of different slices of the 3D model. A volumetric display, like the FELIX 3D Display can solve this problem. It provides space-filling images and is characterized by "multi-viewer" and "all-round view" capabilities without requiring cumbersome goggles.

The FELIX 3D Displays of the swept volume type use laser-light to project real three-dimensional images upwards a rotating screen. Because of some disadvantages using rotating parts in this setup, the FELIX Team started investigations also in the area of static volume displays. The so called, "SolidFELIX" prototypes, have transparent crystals as a projection volume. The image is created by two or one IR-laser beams.

The projected images within all FELIX 3D Displays provide a fascinating, aesthetic impression through their inherent, unique three-dimensional appearance. These features of a 3D display could be combined in an interface between a virtual reality scene and the real world. Real-time interactions and animations are possible. Furthermore, the display could host an intelligent autonomous avatar that might appear within the display volume.

Potential applications as a virtual reality interface include the fields of entertainment, education, art, museum exhibitions, etc.

The FELIX 3D project team has evolved from a scientific working group of students and teachers at a normal high school in northern Germany. Despite minor funding resources considerable results have been achieved in the past.

1 Introduction

Up to today researchers are seeking for ways to display our three-dimensional world in an appropriate way: In all three physical dimensions, interactively, in real time, and in true color. Two-dimensional display systems are still not able to realize depth cues like perspective or hidden contours satisfyingly.

For an ideal dynamic 3D image representation a technique should be preferred with a multiple user, all-round view capability, without the usage of visual aids. It should also satisfy all depth cues such as stereo vision and motion parallax. Volumetric displays, which generate 3D images within a physical volume rather than on a stationary surface, meet most of these needs. The images are thus placed within the

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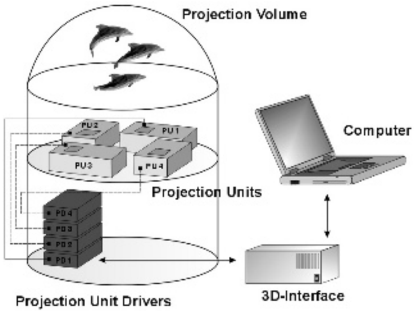

Fig. 1. Modular concept of FELIX 3D display (swept volume)

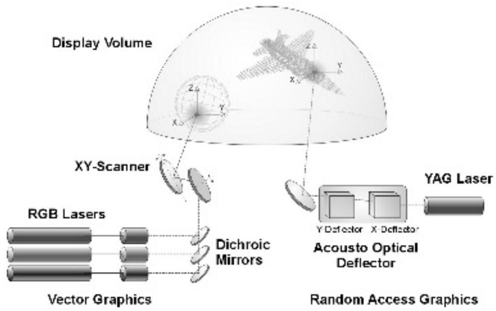

Fig. 2. Different projection techniques for swept volume displays

physical world of the observer, in comparison to virtual reality systems where the observer is placed within the virtual environment of the non-physical image space. The development of all our FELIX 3D Displays is characterized by its comparatively simple system configuration. One or a combination of the three projection techniques can be implemented: vector graphics, raster graphics, random access graphics (Fig. 2).

Moreover all FELIX displays are compact, light, and easy to transport systems of modular design and consist of standard components (Fig. 1).

2 Basic Concepts of Volumetric Imaging

To produce volumetric images, it is necessary to create a display volume of some type within which the image can be drawn. A number of attempts have been made in past and current development efforts. We generally divide these attempts in two basic categories:

- Swept volume displays,
- Static volume displays.

Fig. 7 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 more detail in the following sections. Holographic techniques are not discussed in this paper as they represent a separate class of its own.

2.1 Swept Volume 3D Displays

In the case of swept volume displays, volumetric images can be created within a display volume by reflecting or transmitting light from a moving screen, which is oscillating or rotating. A periodically time-varying two-dimensional (2D) image is used to sweep out the volume cyclically at a frequency higher than the eye can resolve. Eventually a spatial image is formed through persistence of vision. Thus, several of the usual cues of everyday depth perception are exhibited, 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 surface, 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 viewed in an oscillating plane mirror, which has a similar effect.

2.2 Static Volume 3D Displays

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 dots of visible light (so called Volume Pixels or 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.

The phenomenon of stepwise excitation of fluorescence seems to be one suitable and promising approach for the generation of isolated fluorescent voxels.There are two different principles of excitation: Two frequencies, two step (TFTS) upconversion and one frequency, two step (OFTS) upconversion. The TFTS method uses two laser beams of different wavelengths, which intersect within the display material, whereas the OFTS method uses one laser beam of a constant wavelength, which has to be strongly focused to produce a voxel.

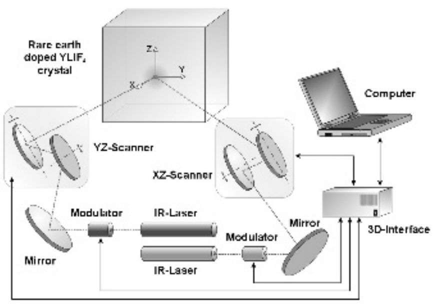

Fig. 3. System Architecture of the SOLID-FELIX 3D Display (static volume; TFTS)

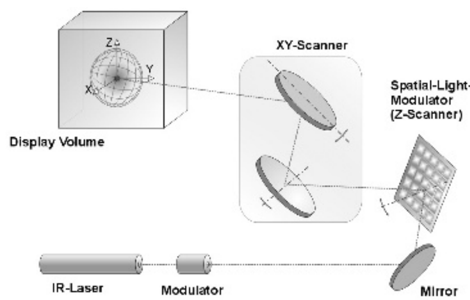

Fig. 4. Principle of a static volume OFTS display, using a spatial-light-modulator[23]

Both techniques are based on the absorption of two photons (normally invisible IR photons) by optically active atoms, molecules or ions. Translucent materials doped with certain ions or phosphors can emit voxels, when exited by two or one infrared laser beams.

In the following sections we will illustrate the past and present developments in the field of volumetric imaging by selecting representative examples for different approaches.

3 Historical Overview

3.1 Swept Volume 3D Displays

Swept volume systems have been discussed theoretically since 1918. However, one of the first functional prototypes of volumetric displays was presented by the early pioneers Parker and Wallis in 1948 using a CRT to create simple 2-D pattern which were projected onto a vibrating mirror or a rotating flat screen. More elaborated techniques, presented by the ITT Laboratories in 1960, consist of an especially programmed high brightness cathode ray tube (CRT) whose blips are optically transferred to a translucent rotating screen within a glass cylinder (Fig. 5). Later, Robert Batchko described a similar system where he used a vector-scanned laser illumination source instead of a CRT. Inspired by these research activities, Gregg Favalora (Actuality Systems, Inc.) recently set up a volumetric display, implementing state-of-the-art hard- and software. A high resolution projection engine illuminates a diffuse projection screen that rotates with projection optics and corresponding relay mirrors.

In another arrangement, introduced by R. Ketchpel in 1962, a phosphor-coated flat screen rotates in a vacuum, with a controlled electron beam striking its surface (Fig. 6). 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.

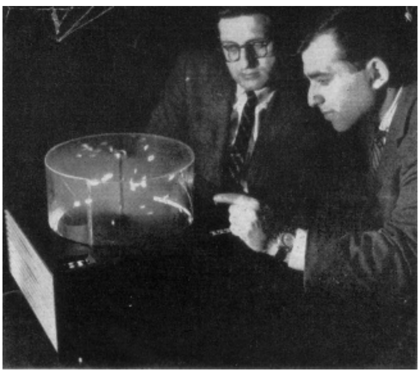

Fig. 5. CRT Projection on rotating screen (ITT, 1960)[17]

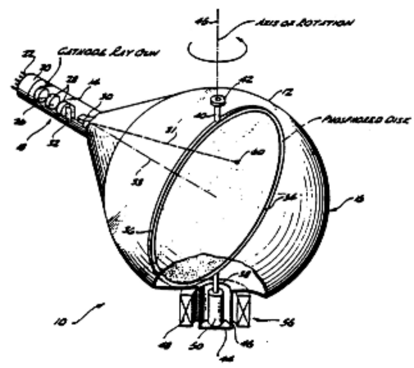

Fig. 6. Rotating phosphor-coated disk in CRT (Ketchpel, 1962)

In 2002 Jang Doo Lee et. al.[4] from Samsung, Korea, presented a paper about “Volumetric Three-Dimensional Display Using Projection CRT”. Within the display they used a flat target screen.

An early approach using a curved moving surface was described in 1962 by D. W. Perkins. He introduced the "spherical spiral display" with a special shaped screen that rotates about its vertical axis and onto which a light beam is projected from below by an optical system. The intention was to use it as a 3D radar display. In 1965 A. M. Skellet filed a patent application with a rotating tilt upward screen.

As a representative of the category of swept volume techniques, we describe the general principle of operation used in our 3D display FELIX. In 1983 we started investigations of different prototypes of the "FELIX 3D Display". These systems refer to the concept of projecting laser images on a rotating screen. Our investigations in this field mainly focus on different screen shapes (helical, double helical, flat), a modular and portable setup, advanced projection techniques and software development.

Volumetric 3D Displays	
Swept Volume Techniques	**Static Volume Techniques**
Flat Surface	*Solid*

– high brightness CRT projection (Parker / Wallis, 1948; ITT Lab. 1960)
– "Generescope" (M. Hirsch, 1958)
– electroluminescent panel (R. J. Schipper, 1961)
– Cathode Ray Tube Imager (R. D. Ketchpel, 1962)
– 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)
– System and Method For High Resolution Volume Display Using a Planar Array (Douglas W. Anderson, et.al 1995)[9]
– Actuality Systems (G. Favalora, 1996)[16]
– CRT (Jang Doo Lee, et. al., 2002)[4]
	– **TFTS upconversion**:
	  – fluorescence in CaF_2:Er^{3+} with use of filtered xenon lamps as excitation sources (J. Lewis et.al., 1971)
	  – Stereoscopic projection technique (E. Luzy and C. Dupuis, 1912)
	  – Display system using rare-earth doped fluoride crystals (M. R. Brown, G. Waters, 1964)
	  – Display system based on simultaneous absorption of two photons (M.A. Dugay, et. al., 1970)
	  – Three-color, solid-state, three-dimensional display (E. Downing, et. al., 1994)
	  – SOLID FELIX 3D Display, 2000[14]
	  – Principle demonstration of 3D volumetric display achieved by PrYb co-doped materials (Xiaobo Chen, et. al., 2000)[13]
	  – Volumetric display based on up-conversion phosphors, (Jianying Cao, et. al., 2005)[22]
	– **OFTS upconversion**:
	  – One-beam pumping of Er^{3+}-doped ZBLAN glasses (T. Honda, 1998)
	  – SOLID FELIX 3D Display, 2000[14]
	  – Dispersed crystallite up-conversion displays (M. Bass, et.al. 2001)[12]
	  – One-beam pumping upconversion volumetric-display (X. Chen, 2002)[19]

Curved Surface	*Gaseous*

– "Spherical Spiral Display" (D. Perkins, 1962)
– “Cathode ray tube for three-dimensional presentations” (A.M. Skellett, 1962)[7]
– helical mirror (W.D.Chase, 1976)
– **helical shaped screen**:
  – de Montebello, 1969
  – Szilard,J., ultra sonics, 1974[6]
  – R. Hartwig, 1976
  – "FELIX 3D-Display", 1983
  – R.D. Williams, 1988 "OmniView"
  – R. Morton, 1990
  – P. Soltan, 1992
  – NEOS Technologies, 1995
  – Zheng J Geng, 2001[8]
  – Live 3-D Video in Volumetric Display (Jung-Young Son, et. al., 2002)[5]
– **Archimedes’ Spiral**:
  – de Montebello, 1969 "Synthalizer"
  – H. Yamada, 1986
	– Intersecting laser beams in Rubidium vapor (E. Korevaar, 1989)
	– Electron beams intersecting in nitrogen gas filled image space (F. S. Howell, 1945)
	– Multiple-step excitation in mercury vapor (R. Zito, Jr., 1962)
	– Two-step excitation of fluorescence in iodine monochloride vapor (R. H. Barnes, et. al., 1974)
	– Imaging phosphor display using voxel activation by two crossing laser beams (E. Downing, B. Torres, 1989)

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

Fig. 7. Overview of volumetric imaging techniques (for detailed references see [1,14])

In the FELIX approach the primary 2D image is generated on a passive projection screen. The rotating screen sweeps out a cylindrical volume. This volume provides a three-dimensional display medium in which scanned laser pulses are projected. The hitting laser beam will be scattered from the rotating surface causing a voxel. 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 screen.

The 2D image is generated by one or more projection units from below the display volume. A projection unit consists of a light source and a XY scanning system. As a light source we use a monochromatic laser as well as a laser-based red-green-blue (RGB) color mixer. Depending on the application we use different types of scanning systems (galvanometric, acousto-optic and micro-electronic-mechanical). Thus, this setup makes it a powerful and flexible tool to keep track with the rapid technological progress of today.[1,2,14,23]

In 1988 R. D. Williams and F. Garcia demonstrated a display wherein a scanned laser beam is displayed upon a continuously 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".

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), in cooperation with NEOS Technologies, works on a similar development as well using a helical surface.

In 2001 Zheng J. Geng[8] filed a patent “Method and Apparatus for an interactive volumetric Three-Dimensional Display” providing a process and system for interactively displaying large (more than one million voxels) volumetric 3D images utilizing a sequence of helical slices of a 3D data set. Core elements of his setup are a spatial light modulator and a helical target screen.

3.2 Static Volume 3D Displays

The effect of TFTS upconversion has been known since the 1920s, when it was first observed in mercury vapor, later it was used for 3D laser display approaches.

Based on the pioneering work of J. D. Lewis et. al. of Batelle Laboratories in 1971, 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.

Another approach, patented by E. J. Korevaar in 1989, used a gaseous volume enclosed in a sealed glass container.

In 1998 Honda investigated the quantum efficiency for OFTS upconversion in 0.2 mol% Er^{3+} doped ZBLAN glass. This alternative excitation method uses one focused laser beam at a wavelength of 979 nm.

Since 1999 the FELIX team is also investigating static volume approaches.Core element of our setup is the display volume, which consists of a cubic transparent material (glass or crystal), doped with ions from the rare earth-group of the elements. In our case the primary dopant is Er^{3+} in a concentration of 0.5 mol%. These ions are excited in two steps by one (OFTS) or two (TFTS) infrared laser beams. Initial tests with our experimental setup, called "Solid FELIX", revealed promising results.[23]

In 2001 M. Bass[12] from the University of Central Florida filed a patent for a OFTS static 3D volume display in which a dye doped display medium is used, where the

Miscellaneous	
– stylus in gelatine material (Chrysler, 1960) – 3D fiber optic display (A. Gery, 1983) – voxel addressed by optical fiber (D. L. Macfarlane, 1994) – field-sequential projection on stacked electrically switchable mirrors (T. Buzak, 1985) – scattering LC-display (Q. Luo, et. al.) – Intersecting electron beams in a phosphor particle cloud (W. G. Rowe, 1975) – 3D optical memory (D. A. Parthenopoulos, P. M. Rentzepis, 1990)	– layered LC-based 3D display using one light source (M. S. Leung, et.al., 1998) – layered LC-based 3D display with several light sources (R. S. Gold, J. E. Freeman, 1998) – Multi-planar volumetric display system using psychological vision cues (Sullivan, et. al.,2001)[11] – Development of 3-D display system by a Fan-like Array of Projection Optics (Toshio Honda, et. al., 2002)10 – 3D Display using parallax barrier: "The SeeLinder" (T. Yendo, 2004)

Fig. 8. Miscellaneous volumetric display techniques[1]

emitting particles are dispersed in a transparent host (acrylic plastic or glass). He proposed a spatial light modulator to scan the focus fast enough through all three dimensions of the display cube.

In the following years extensive and elaborated research work on static volume 3 D displays was done by Xiaobo Chen, et. al.,[19,20,21] from Beijing Normal University and Institute of Physics (China) concerning appropriate materials as well as different excitation methods (OFTS and TFTS),scanning methods and multiple color mixing.

Apart from the described technologies several other 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.

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-cured optical resin doped with an organic dye. Each voxel is addressed by an optical fiber that pipes light to the voxel.

4 Interface Techniques

A basic problem of interactive virtual reality is the interface between the virtual 3D world and the real 3D world. All current known standard interfaces are only 2D interfaces, like a flat monitor or the computer mouse. Reducing 3D to 2D always means losing information. An approach of solving this problem is the usage of 3D interfaces.

Volumetric 3D displays will take the first barrier, the reduction of the third dimension of the displayed scene. The communication and interaction with the virtual reality will also be increased by using such a display. Projecting a real 3D image boosts the number of interaction methods and devices. Many solutions and approaches were presented in the past, but mainly as theoretical ideas. Only a few 3D interfaces came on the market. Most of the launched interfaces are focused in the area of CAD.

Fig. 9. Dolphins swimming through the display

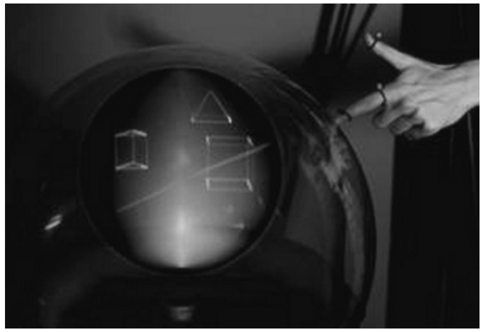

Fig. 10. Multi-finger gestural interaction device using visual tracking methods[18]

A direct interaction with the volumetric display should not require any additional interface devices, like a mouse, a keyboard or a additional flat monitor. In our opinion, visual tracking techniques are the most desirable approaches, because of their advantages of intuitive interaction. For instance, the visual tracking of hand gestures is qualified for 3D interactions, due to the fact that people use additional gestures to express things, feelings and shapes, they are talking about.

The FELIX group started investigations in the field of input devices and interaction possibilities. As an input device for volumetric displays we discussed a six degrees of freedom device, operating in three dimensions. The device is mechanically connected to the display's mounting and connected to the user's arm-wrists. Sensors track the motion and forces of the users hand or arm and translate it to commands for the display.[1] To improve the interactive use of volumetric displays we also worked with avatars, using artificial intelligence. The vision is to create a three dimensional head in the display, which acts and behaves like a human being.[15]

Balakrishnan et. al.[3] summarized the features of different user interface approaches and discussed the interface design by using physical mockups. They recommend "separated spaces" (display volume and interface volume are separated) for interface approaches and also discuss nonhaptic interaction, like eye-tracker and voice controlling.

As a conclusion it can be said that an interface for a volumetric display should be highly interactive and must consider that people got used to interact with a real 3D world in their normal life. A 3D Interface should adapt as many as possible of these interacting techniques to offer an intuitive handling of the controlled virtual 3D world.

5 Areas of Application

Spatial visualization of data can simplify and accelerate the working process. As described above, volumetric displays can be used as an interface for interactive virtual 3D scenes. With an adequate 3D user input device, following applications are possible:

- Scientific visualization: *Projection of multi-dimensional data structures*
- Entertainment: *Demonstration of FELIX as an interactive 3D play-console*

- Computer Aided Design: *Collision analysis for virtual mockups*
- Chemistry/physics/pharmacy: *Visualization of molecular structures*
- Medical Imaging: *Display of 3D ultrasonic pictures*
- Air Traffic Control: *3D visualization of a typical air traffic scenario*
- Interface for virtual reality: *highly interactive interface device*

Fig. 11. Animated models in the Felix 3D display

Fig. 12. Possible scenario: Discussion with a 3D avatar in the volumetric display

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