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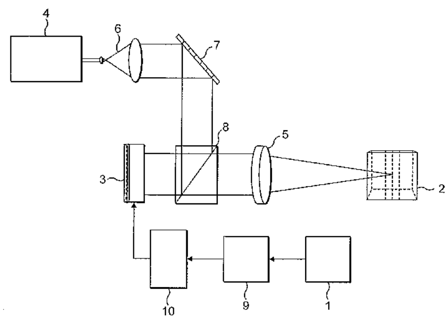
(54) Title: THREE DIMENSIONAL DISPLAYS



(57) Abstract: A 3D projection display system uses a holographic arrangement to produce a three dimensional real image of a CAD solid model displayed on a CAD workstation (1) in a scattering medium (2). Successive cross-sectional level slice images through the CAD solid model are displayed as holograms on a liquid crystal spatial light modulator (3), which is illuminated with a coherent read-out beam from a laser diode source (4) to "read-out" the holograms as they are displayed such that the corresponding cross-sectional image is reconstructed at the desired z-axis position within the scattering medium (2). To achieve the necessary complex encoding of the holograms to be displayed on the spatial light modulator (3), the pixels of the spatial light modulator (3) are arranged in pairs as "macropixels", with one pixel of each pair being used to represent the real component of the complex wavefront at that particular pixel location, and the second pixel of each pair being used to represent the imaginary component of the wavefront at that pixel location. The display of the cross-sections on the spatial light modulator (3) is time multiplexed and repeated in an appropriate manner to allow persistence of vision to give the illusion of a full three dimensional image in the scattering medium (2).

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Three Dimensional Displays

The present invention relates to three dimensional displays and in particular to the generation of such displays using holographic techniques.

The display of fully three dimensional images can be of value in a number of fields, for example to aid the visualisation of complex three dimensional shapes in the field of engineering design, or to display parts of the anatomy of a patient for planning surgical procedures in the medical field. The display of fully three-dimensional images is also becoming increasingly desirable for entertainment purposes, for example in the context of interactive video games.

One current technique for generating three dimensional displays is to use so-called "stereo" displays in which two images seen from a different perspective are displayed separately to each eye. However, such displays do not yield an objective three dimensional image, because the three dimensional effect is only "produced" in the brain of the viewer.

Other proposals for producing three dimensional displays use holographic techniques. The advantage of a holographic display is that as well as producing a virtual image that can be viewed as a three dimensional object by a viewer, it also produces a real image that can be bought to a three dimensional focus in a scattering medium, such as Agarose gel, to create an objective three dimensional display that appears to "float" in space. Quantitative measurements are possible on this real image and, with a suitable display, it is possible to "walk" around the image to view different aspects of it.

In already proposed holographic three dimensional display techniques, the three dimensional display is built up as a series of "slices" that are projected into different planes in space using a hologram to control the plane of imaging. The holograms are usually displayed on a spatial light modulator (SLM) or similar device that is then illuminated with a fully coherent light source such as a laser so as to "read out" the hologram and display the corresponding image (slice) at the desired point in space, as is known in the art. These known methods either use conventional carrier wave holograms that are recorded directly onto an (positive-only) amplitude modulating spatial light modulator, or used a phase-only modulating SLM to record a phase-only hologram (kinoform).

However, the latter technique requires the phase distribution for each hologram to be calculated by computationally intensive iterative techniques. It is therefore, for example, not suitable for "real-time" displays.

In the carrier wave hologram technique, the complex wavefront necessary to produce the hologram is recorded on a carrier wave (as in an optically recorded hologram), i.e. the real amplitude is represented by a width of the fringe pattern and the phase is represented as a position modulation of the fringe pattern. This requires a significant amount of data if a high resolution (and hence a high quality image) is to be achieved. Furthermore, existing techniques for encoding such carrier wave holograms onto spatial light modulators are relatively inefficient and low resolution.

This accordingly limits the performance achievable using a carrier wave hologram technique, for example with regard to the complexity of the object that can be recorded and reconstructed, and the quality of the reconstructed image. Furthermore, such carrier wave holograms are usually thin transmission binary holograms which, as is known in the art, have low reconstruction efficiency.

Thus the Applicants believe that there remains scope for improved techniques for holographically generating three dimensional displays.

The Applicants have previously proposed in their papers "Fully Complex Optical Modulation using an Analogue Ferroelectric Spatial Light Modulator", P.M. Birch, R.C.D. Young, D.M. Budgett, C.R. Chatwin, Optics Communications, Vol. 175, pp. 347-352, March 2000, and "Two pixel computer generated hologram using a zero twist nematic liquid crystal spatial light modulator", P.M. Birch, R.C.D. Young, D.M. Budgett, C.R. Chatwin, Optics Letters, Vol. 25, No. 14, pp. 1013-1015, 2000, a technique for generating full complex modulation in the Fourier plane using an analogue ferroelectric liquid crystal spatial light modulator.

In this technique, the complex wavefront at any given location is represented by using two pixels of the spatial light modulator together as a "macro" pixel, with one of the pixels representing the real component of the amplitude of the complex wavefront at that pixel location and the other pixel representing the imaginary component of the amplitude of the wavefront at that pixel location. The imaginary component is $\pi/2$ phase shifted from the real component using a phase detour technique.

The Applicants have now recognised that this technique that they have previously proposed can, with appropriate modifications, be used to provide improved holographic three dimensional displays.

In particular, the Applicants have recognised that if the Fresnel transform of the object to be displayed is displayed on the spatial light modulator using their above previously proposed technique, then that allows the corresponding light distribution for displaying the object to be projected to an exact plane. This is because a Fresnel transform, as well as describing the relation of the complex amplitude of the wavefront between front and back focal planes of a converging lens like a Fourier transform, also contains a quadratic phase curvature term that is z-axis dependent (i.e. for a given value of z it gives the light distribution in a plane displaced by "z" away from the front focal plane). Thus by calculating and displaying on the spatial light modulator different Fresnel transforms the holographic reconstruction can be projected to different planes in space.

The Applicants have further recognised that displaying the Fresnel transform of the object to be displayed on the spatial light modulator using their above previously proposed technique is much more efficient in terms, e.g., of the way in which the data is encoded onto the spatial light modulator, as compared, e.g., to previous carrier wave hologram techniques. This accordingly facilitates improved image reconstruction quality, and the more rapid projection of successive planes or slices of an image to be reconstructed to a given region in space using a spatial light modulator or similar device, thereby allowing a three dimensional image to be achieved through persistence of vision effects.

Thus, according to a first aspect of the present invention, there is provided a method of generating a three dimensional image of an object, comprising:

dividing a representation of an object to be imaged into plural successive cross-sectional slices;

determining a Fresnel transform for each slice;

displaying the Fresnel transform for each successive slice on a spatial light modulator by representing the real component of the complex amplitude of the Fresnel transform at a given location on the spatial light modulator on one pixel of the spatial light modulator at that location and representing the corresponding imaginary component of the complex amplitude of the Fresnel transform at that location on a second pixel of the spatial light modulator at that location;

illuminating the spatial light modulator such that the Fresnel transforms displayed on the spatial light modulator modulate the illuminating light beam; and

repeating the display and illumination of each Fresnel transform on the spatial light modulator sufficiently frequently so as to allow a three dimensional display of an image of the object through persistence of vision effects to be achieved.

According to a second aspect of the present invention, there is provided an apparatus for holographically displaying a three dimensional image of an object, comprising:

a spatial light modulator in which pairs of pixels of the spatial light modulator are associated with each other;

means for displaying on a first pixel of a pair of associated pixels of the spatial light modulator, the real component of the complex amplitude of an optical wavefront to be displayed at that location on the spatial light modulator and for displaying on the second pixel of the pixel pair the corresponding imaginary component of the complex amplitude of the optical wavefront at that location;

means for dividing a representation of an object to be imaged into plural successive cross-sectional slices;

means for determining a Fresnel transform for each slice;

means for displaying the Fresnel transform for each successive slice on the spatial light modulator by representing the real component of the complex amplitude of the Fresnel transform at each given location on the spatial light modulator on the first pixel of the pair of associated pixels of the spatial light modulator at that location and by representing the corresponding imaginary component of the complex amplitude of the Fresnel transform on the associated, second pixel of that pixel pair of the spatial light modulator;

means for illuminating the spatial light modulator such the Fresnel transforms displayed on the spatial light modulator modulate the illuminating light beam; and

means for repeating the display and illumination of each Fresnel transform on the spatial light modulator sufficiently frequently so as to allow a three dimensional image of the object to be achieved through persistence of vision effects.

The present invention uses the Applicants' previously proposed technique for representing a fully complex wavefront on a spatial light modulator to display successive Fresnel transforms of "slices" of the image to be displayed to build up a fully three dimensional image by persistence of vision effects.

As discussed above, an advantage of the present invention is that the data necessary for the display can be loaded onto the spatial light modulator in a more efficient manner. This accordingly means that more of the available data handling capacity of the spatial light modulator can be used to control both the phase and amplitude of the image across the plane of the spatial light modulator (such that, e.g., a higher resolution can be achieved), thereby allowing higher holographic reconstruction quality (and accordingly higher quality three dimensional images). It also means that the frame rate for the image (i.e. the frequency with which the "slices" of the image displayed on the spatial light modulator can be changed) can be made correspondingly faster. This in particular makes it feasible to drive the spatial light modulator at a sufficiently high frame rate to achieve a three dimensional display through persistence of vision, while still maintaining a relatively high reconstructed image quality.

Furthermore, the Fresnel transform that is displayed on the spatial light modulator can be related to the desired reconstruction by a single Fourier transform, such that the required hologram can be rapidly computed.

This further facilitates a more rapid frame rate and higher quality for the display. The ability to rapidly compute the required holograms for the display also facilitates the possibility of generating the three dimensional display in real-time and interactively, e.g. from a CAD display. This would allow, for example, the holographic display to be rotated and re-computed in real-time as a user re-orientates the corresponding model on a CAD display.

In the present invention, a representation of the object to be imaged is divided into cross-sectional slices. Thus, in effect, the image to be displayed is divided into cross-sectional slices. This division can be done as desired. In a preferred embodiment, the three dimensional light volume of the representation of the object (i.e. of the image to be displayed) is divided into slices along a z-axis that points normal to the face of the spatial light modulator.

The representation of the object to be imaged can also be derived as desired. In a preferred embodiment it is in the form of an electronic representation of the object, such as a CAD model as discussed above. However, other techniques for representing the object that can be used with the present invention could also be used, if desired.

The way that the two dimensional cross-sectional slices of the image are converted to Fresnel transform holograms for display on the spatial light modulator can again be selected as desired. In a particularly preferred embodiment, each Fresnel transform hologram is determined by applying an appropriate quadratic phase factor to the Fourier transform of the required cross-sectional intensity pattern. This allows the Fresnel transform to be related to the desired reconstruction by a single Fourier transform.

The spatial light modulator that is used can be any suitable such device that can be encoded in the manner of the present invention. It can be a reflective or transmissive device. The spatial light modulator preferably includes a fast effect liquid crystal and is preferably designed for high-speed addressing. It can preferably achieve frame rates of the order of several thousand (such as four thousand or more) frames per second when driven in accordance with the present invention. A frame rate of four thousand frames per second would, for example, allow two hundred layers to be displayed and fully updated twenty times a second, which would provide adequate z-axis resolution and up-date speed to give a fully three dimensional display.

The spatial light modulator is preferably multi-level addressable (rather than, e.g., binary addressable). It could be a digital multi-level device, or an analogue device. In a preferred embodiment it has an analogue backplane. Such multi-level addressing can be achieved, e.g., through electrical addressing of a reflective or transmissive device, as is known in the art. A reflective silicon device that can be analogue addressed via a silicon backplane would, for example, be suitable.

The spatial light modulator is most preferably capable of bipolar amplitude modulation (i.e. positive and negative amplitude modulation). Thus, when a liquid crystal device is used, the liquid crystal type preferably allows bipolar amplitude modulation (i.e. it modulates along the real axis).

Both of the above properties facilitate addressing the spatial light modulator in the manner required by the present invention, and in particular facilitate the ability to rotate the phasor to be displayed on the spatial light modulator and the ability to achieve full complex modulation using only two pixels of the spatial light modulator at any given location.

In a particularly preferred embodiment, the spatial light modulator is in the form of an analogue ferroelectric liquid crystal spatial light modulator. Analogue ferroelectric liquid crystal spatial light modulators have higher switching speeds (of the order of 200 ns) compared to nematic liquid crystals (which have switching speeds of the order of 20 ms) and so are particularly suited to use for the present invention. Most preferably the spatial light modulator comprises an analogue silicon backplane addressing a ferroelectric smectic A* or C* liquid crystal layer. (As is known in the art, a ferroelectric smectic A* liquid crystal layer is truly analogue addressable, and a ferroelectric smectic C* liquid crystal layer, although inherently binary, can be used in an analogue manner.)

Once the Fresnel transforms have been determined, they should then be encoded for display on the spatial light modulator. As discussed above, the present invention represents the real component of the Fresnel transform at any given location on one pixel of a pixel pair and the imaginary component on the other pixel of the pixel pair (i.e. such that only two pixels of the spatial light modulator are necessary to represent the entire Fresnel transform at that location). The pixels of each pixel pair should be adjacent and are preferably contiguous.

Thus the complex field distribution of each Fresnel transform should be "two-pixel" encoded, such that for each given "location" on the spatial light modulator, one pixel represents the real component of the complex wavefront at that point, and the other associated pixel represents the imaginary component of the complex wavefront at that point.

As will be appreciated by those skilled in the art, the imaginary component of the complex wavefront should be orthogonal to (i.e. $\pi/2$ phase-shifted from) the real component. This can be achieved in any suitable manner.

In a particularly preferred embodiment, the orthogonal relationship between the real and imaginary components is achieved by arranging the system such that, as seen from the image reconstruction, there is a $\pi/2$ phase difference between the modulated wavefront from the pixel representing the imaginary component and the modulated wavefront from the pixel representing the corresponding real component of each pixel pair, i.e. such that there is effectively a relative $\pi/2$ phase lag between the two pixels of each pixel pair.

In a particularly preferred such arrangement, a phase detour technique is used to achieve this $\pi/2$ (or any other necessary) relative phase shift between the real and imaginary components. The phase detour is preferably achieved by reconstructing the image at an angle to the plane of the spatial light modulator such that there is when viewed from that angle, a $\pi/2$ phase lag between adjacent pixels. In other words, the spatial light modulator is, in effect, tilted by an angle such that there is a phase lag of $\pi/2$ between adjacent pixels.

In a preferred such arrangement, the data on every second real and imaginary pixel pair is multiplied by -1, as this can help to avoid any undesirable secondary reconstruction in the output plane (such secondary reconstruction can occur because with the phase detour technique, adjacent pixel pairs will in fact be π out of phase with each other).

In a particularly preferred embodiment, the system is arranged so as to ensure that the displayed Fresnel transforms are displayed such that at each pixel location on the spatial light modulator, the image displayed has a one-to-one aspect ratio, i.e. the overall "pixel" width (i.e. including both the real and imaginary components) at that location is the same as the overall "pixel" height. This could be achieved, e.g., by arranging the spatial light modulator such that its individual pixels have an aspect ratio of two-to-one, i.e. such that a real component pixel and an imaginary component pixel side-by-side (i.e. the pixels of a pixel pair) would have the same width as their height.

Alternatively, where the individual pixels of the spatial light modulator are square (have a one-to-one aspect ratio) two sets of identical real and imaginary pixel pairs are preferably encoded onto the spatial light modulator side-by-side, so as to form a "super-pixel" comprising four pixels in a square that accordingly has the same width as its height. In this arrangement, the pixels are effectively "doubled-up", i.e. the same data is placed on two contiguous pixels in a direction orthogonal to the direction of the line joining the real component pixel and the imaginary component pixel of a pixel pair, so as to form a symmetrical "super-pixel" made up of four individual pixels.

The encoded Fresnel transforms of the cross-sectional slices are loaded onto the spatial light modulator in turn so as to build up the three dimensional display. This can be done as desired. The order in which the "slices" are displayed on the spatial light modulator need not necessarily be such that immediately successive slices are displayed immediately one after another; other orders of display could be used if desired. For example, the slices could be interleaved in some manner. This may help to reduce flicker in the reproduced image.

It would also be possible to display more than one cross-sectional slice on the spatial light modulator at the same time, if desired (where the spatial light modulator is capable of doing so). Indeed, it is preferred in some circumstances for the spatial light modulator to display plural cross-sectional slices of the image simultaneously. Many spatial light modulators support multiple-bit addressing (for example have a dynamic range of up to 8 bits). Such spatial light modulators would be able to display a Fresnel transform hologram that comprises multiple cross-sectional slices multiplexed into a single Fresnel transform hologram so that the cross-sectional slices can be displayed simultaneously.

The technique of the present invention facilitates such simultaneous superimposition of Fresnel transforms for different cross-sectional slices because, as it uses complex amplitudes (such that any superimposition, summing, etc., of the Fresnel transform holograms is linear), the effect of adding two Fresnel transform holograms to give a single hologram to be displayed on the spatial light modulator is that the two individual holograms will be reconstructed at the two planes that they correspond to. This means that more than one "slice" can be displayed on the spatial light modulator simultaneously, without affecting the reproduction of those slices in the reconstructed image.

Superimposing several cross-sectional slices onto the spatial light modulator in this way and displaying them simultaneously, allows multiple planes of the image to be reconstructed simultaneously. Such arrangements would facilitate further flexibility between, e.g., the dynamic range requirements of the spatial light modulator (i.e. how much data it can hold and display on a single frame), the resolution in the z-axis (i.e. the number of cross-sectional slices into which the projected image is effectively decomposed), and the repetition rate of the display. For example, where the spatial light modulator permits, it would be possible to display the entire image simultaneously (in one go). This would in effect produce a full, static hologram (which can be considered to be the projection of all cross-sectional slices simultaneously).

The cross-sectional slices are "read-out" from the spatial light modulator by illuminating the spatial light modulator such that the displayed Fresnel transforms modulate the illuminating light beam in an appropriate manner. The illuminating light beam can be modulated by it either being reflected by the spatial light modulator or by it being transmitted through the spatial light modulator (depending on whether the spatial light modulator is a reflective or transmissive device), as is known in the art. The illuminating light beam is preferably a fully coherent light source, such as a laser.

The effect of illuminating the spatial light modulator in this way is that a modulated wavefront is produced that effectively projects the corresponding Fresnel transforms of the cross-sectional slices to a given point in space. Thus, the illumination is preferably arranged such that the Fresnel transforms of the cross-sectional slices are projected to a desired point in space.

The so-modulated illuminating beam must then be transformed to an image that can be viewed. This can be done in any suitable manner, such as by passing it through a converging, e.g. Fourier, lens or lens system to reconstruct the corresponding image at the desired point in space.

Thus, the spatial light modulator is preferably illuminated with a fully coherent light source, preferably a laser, with the so-modulated reflected (or transmitted) coherent illumination then being passed through a converging, preferably Fourier, lens to reconstruct the image(s) of the cross-section(s) at the desired z-axis position. In other words, the Fresnel transforms displayed on the spatial light modulator are projected through a converging lens into space which transforms them into the (space domain) image of the corresponding image cross-section at the correct z-axis position in space that corresponds to that level-slice position in the original representation of the object to be imaged.

As discussed above, the full three dimensional display is generated by displaying the cross-sectional slices of the image at a sufficiently fast repetition rate for persistence of vision to create the impression of a complete image. Thus the display of the different cross-sectional slices should be arranged so as to, e.g., repeat sufficiently rapidly for persistence of vision to give a fully three dimensional image. Thus, the repeat time for each cross-sectional slice is preferably about 40 msec or less.

The three dimensional display can be viewed in any appropriate manner. Thus it could, for example, be viewed as a virtual image by placing the eye looking into the spatial light modulator (with appropriate guarding from the undiffracted light from the spatial light modulator). In a preferred embodiment, the image is displayed as a real image in a scattering medium, such as Agarose gel.

As discussed above, a significant advantage of the present invention is that because it encodes the data to produce the display onto the spatial light modulator in a more efficient manner, it facilitates the provision of a substantially real-time, interactive, three-dimensional display.

Thus, in a particularly preferred embodiment, the display can be controlled and manipulated by a user, and most preferably can be updated substantially in "real-time" in response to user commands. This could be achieved, for example, by using the system of the present invention to display a three dimensional model displayed on a CAD workstation, and updating the display as the user interacts with and moves the model on the CAD display.

In such an arrangement, a real-time software implementation is preferably used to calculate the z-axis cross-sectional slices through the solid CAD model corresponding to its current orientation and then a 2-D FFT (Fast Fourier Transform) engine used to calculate the Fresnel hologram corresponding to each cross-sectional slice, with the resulting holograms then being displayed on the spatial light modulator at a sufficiently high frame rate. This would allow a fully interactive, three-dimensional display to be generated, substantially in real-time, of the solid CAD model. Furthermore, since a real image of the CAD model can be produced, quantitative measurements can be made on the image, and, e.g., fully three dimensional manipulations planned for applications such as complex surgery or the fitting of two manufactured items together.

It is believed that such an arrangement may be new and advantageous in its own right. Thus, according to a third aspect of the present invention, there is provided a method of generating a three dimensional image of a CAD solid model, comprising:

dividing a CAD solid model into plural successive cross-sectional slices;

determining a Fresnel transform for each cross-sectional slice;

displaying the Fresnel transform for each successive slice on a spatial light modulator;

illuminating the spatial light modulator such that the Fresnel transforms displayed on the spatial light modulator modulate the illuminating light beam; and

repeating the display and illumination of each Fresnel transform on the spatial light modulator sufficiently frequently so as to allow a three dimensional display of the CAD solid model through persistence of vision effects to be achieved.

According to a fourth aspect of the present invention, there is provided an apparatus for holographically displaying a three dimensional image of a CAD solid model, comprising:

a spatial light modulator;

means for dividing a CAD solid model to be displayed into plural successive cross-sectional slices;

means for determining a Fresnel transform for each cross-sectional slice;

means for displaying the Fresnel transform for each successive slice on the spatial light modulator;

means for illuminating the spatial light modulator such that the Fresnel transforms displayed on the spatial light modulator modulate the illuminating light beam; and

means for repeating the display and illumination of each Fresnel transform on the spatial light modulator sufficiently frequently so as to allow a three dimensional image of the CAD model to be achieved through persistence of vision effects.

As will be appreciated by those skilled in the art, these aspects of the invention can include any one or more or all preferred and optional features of the present invention described herein.

In a preferred embodiment, the system is arranged to produce a colour three dimensional display. This can be achieved, for example, by dividing each cross-sectional slice of the image into plural colour segments (preferably three, red, green and blue, as is known in the art) and deriving the Fresnel transform for each colour segment. By then illuminating each colour segment hologram when it is displayed on the spatial light modulator with coherent light of the appropriate wavelength (colour), a colour reconstruction of the image can be achieved.

Such an arrangement could use a single spatial light modulator which is illuminated in succession with the different wavelengths of light (with the appropriate colour segment hologram(s) being displayed on the spatial light modulator during the corresponding wavelength exposure for the particular cross-sectional slice(s) being reconstructed at that time).

Alternatively, three separate spatial light modulators could be used, each simultaneously displaying a colour channel for the cross-sectional slice(s) currently being displayed, and being illuminated by light of the corresponding wavelength. Dichroic optics could then be used to combine the modulated wavefronts from each spatial light modulator into a single multispectral beam which can then be passed through an achromatic Fourier lens system to generate the holographic reconstruction.

In such "colour" display arrangements, the phase retardance of the spatial light modulator is preferably adjusted to compensate for the wavelength shifts for the (three) colours being used. This could be done, e.g., by prior calibration of the spatial light modulator's dispersion characteristics.

Although it would be necessary in such arrangements for producing a colour display to derive (and display) additional Fresnel holograms (one for each colour), it is believed that the present invention facilitates such colour display arrangements because the hologram calculation and spatial light modulator addressing of the present invention is more efficient.

In a particularly preferred embodiment, steps for or means for reducing or ameliorating the problem of "speckle" in the reconstructed image are taken. (As is known in the art, speckle noise can arise where a fully coherent light source is used to reconstruct a holographic image.) In the present invention, speckle should not be a problem between cross-sectional slices produced by successive spatial light modulator frames since those slices will not cohere. However, there could be speckle contamination within a given cross-sectional slice. Steps are accordingly preferably taken to reduce or ameliorate the speckle.

In one preferred embodiment, this is achieved by effecting a slight mechanical movement of the scattering medium, as this will tend to average out the speckle over the short period during which the frame is reconstructed. Such movement could be provided, e.g., by mounting the scattering medium on a piezo-electric transducer or similar device that can be used to induce a small mechanical motion. Other techniques for ameliorating speckle could be used if desired.

These techniques could also be employed where a full colour hologram is being reconstructed, although in that case they may be unnecessary, as each coloured illuminating beam from the separate lasers will be mutually incoherent, and the (three) successive pulses of each colour will tend to average out the speckle from each beam.

In a particularly preferred embodiment, the holograms generated using the spatial light modulator in accordance with the present invention are recorded into a volume holographic medium, most preferably such a medium that is dynamically and/or repeatedly recordable and erasable, such as a photorefractive crystal, such as Bismuth Silicon Oxide or Lithium Niobate, from where they can then be read out to give the three dimensional display. This is preferably carried out by using the storage capacity of the holographic medium to record multiple successive holograms, each corresponding to a cross-sectional slice (or slices) through the image to be reconstructed.

The multiple holograms can be recorded as desired in the holographic medium. They are preferably stored as superimposed angle multiplexed volume holograms in the holographic medium. They should be recorded using a fully coherent source (such as a laser), as is known in the art. The angle multiplexing can be achieved, e.g., by changing the angle of the recording reference beam by a small amount between successive exposures so that each hologram is recorded on a different carrier frequency.

In such an arrangement, each hologram can then be reconstructed by scanning a collimated (white light) reference beam (i.e. that is spatially coherent but temporally incoherent) through the same set of angles as the recording reference beam to reconstruct a real image in the scattering medium at successive planes, thereby creating the illusion of a three dimensional image floating in free space to a human observer.

As this arrangement allows the three dimensional image to be reconstructed from the volume hologram using a white light source that is temporally incoherent, speckle noise will not be introduced into the reconstruction, and the reconstruction quality may therefore be higher.

Indeed, it is believed that providing a three dimensional holographic display that can be displayed using a collimated white light source in this way may be new and advantageous in its own right. Thus, according to a fifth aspect of the present invention, there is provided a method of recording in a volume holographic medium a hologram for generating a three dimensional image of an object, comprising:

dividing a representation of an object to be imaged into plural successive cross-sectional slices;

determining a near field hologram for each slice;

displaying the near field hologram for each successive slice on a spatial light modulator;

illuminating the spatial light modulator such that the displayed near field holograms modulate the illuminating light beam;

reconstructing the corresponding image in the volume holographic medium; and

simultaneously illuminating the volume holographic medium with a coherent recording reference beam so as to record the projected reconstructed images in the volume holographic medium.

According to a sixth aspect of the present invention, there is provided an apparatus for recording in a volume holographic medium a hologram for generating a three dimensional image of an object, comprising:

means for dividing a representation of an object to be imaged into plural successive cross-sectional slices;

means for determining a near field hologram for each slice;

means for displaying the near field hologram transform for each successive slice on a spatial light modulator;

means for illuminating the spatial light modulator such that the displayed near field holograms modulate the illuminating light beam;

means for reconstructing the corresponding image in the volume holographic medium; and

means for simultaneously illuminating the volume holographic medium with a coherent recording reference beam so as to record the projected reconstructed images in the volume holographic medium.

As will be appreciated from the above, these aspects and embodiments of the invention can and preferably do include any one or more or all of the preferred and optional features of the invention described herein. Thus, for example, the near-field holograms (holographic transforms) generated for each cross-sectional slice preferably comprise Fresnel holograms, that are then displayed on the spatial light modulator, preferably in the manner discussed above. Similarly, it is preferred for the different cross-sectional slices to be angle multiplexed within the volume holographic medium. The recorded volume hologram is also preferably read out from the volume holographic medium using a collimated white light reading beam, when the image is to be reconstructed.

The present invention also accordingly extends to a volume holographic medium storing a hologram that has been recorded using the method or apparatus of the present invention.

Although the present invention has been described above with reference to producing a three dimensional display of an image, as will be appreciated by those skilled in the art, what effectively is happening is the generation of a three-dimensional light distribution at a desired point in space. Such a light distribution can, as discussed above, reproduce a desired image to be viewed, but could also be used for other purposes where it is desirable to be able to generate and control a given three dimensional light distribution.

For example, optical "tweezers" are an important technique in several fields, including the micro-manipulation of biological cells, and in colloidal physics for colloidal transport and the direct nanofabrication of materials. In the latter case, large three dimensional spot arrays in which the individual elements can be individually controlled in three dimensions are used. In biological applications, multiple focussed beam spots that can be moved independently anywhere within an arbitrary three dimensional volume are used to support and manipulate cells and sub-cellular components by photon pressure.

It is also known in cold atom research to generate optical traps in the form of complex three-dimensional light surfaces to form a blue-detuned dipole trap for, e.g., confining and manipulating atoms and Bose-Einstein condensates in a controlled manner.

The techniques of the present invention can be used to generate the appropriate three dimensional light distributions for use in such optical trapping and manipulating applications, for example to generate the spot arrays (optical "tweezers") necessary for cell manipulation.

Indeed a significant advantage of the present invention is that the efficient hologram encoding technique of the present invention, together with the fact that there can be a direct Fourier relationship between the wavefront modulated by the spatial light modulator and the intensity pattern desired in the working volume of the optical manipulator (i.e. the projected light distribution) (such that the hologram corresponding to the desired intensity distribution in the working plane of the optical manipulator can, as discussed above, be explicitly calculated by a single two dimensional Fourier transform), facilitates, as discussed above, fully interactive light beam manipulations in response to user commands in real-time.

Thus the present invention also extends to the use of the methods or apparatus of the present invention for generating (and controlling the motion of) multiple optical beams, for, e.g., optical tweezer manipulation applications.

The system of the present invention has similar advantages in the context of cold atom optics and for producing cold atom confinement traps. In particular, as the present invention facilitates the generation of arbitrary three dimensional light distributions, it can, e.g., be used to generate more complex structures, such as bottle beams, which would be desirable for confining cold atom condensates. It should be noted in this regard that the generated light distribution does not have to be continuously in place to maintain confinement, rather a one thousand Hertz (or more) refresh rate would be adequate to do so. Where this cannot be achieved by a single spatial light modulator alone, then additional techniques could be used. For example, multiple spatial light modulators, each generating a portion of the desired light distribution, could be used. This type of arrangement could be based on, for example, the colour display spatial light modulator arrangement using plural spatial light modulators discussed above.

Thus the present invention also extends to the use of the methods or apparatus of the present invention for producing cold atom confinement traps.

Similarly, according to a seventh aspect of the present invention, there is provided a method of generating a three dimensional light distribution, comprising:

dividing a desired light distribution into plural successive cross-sectional slices;

determining a Fresnel transform for each cross-sectional slice;

displaying the Fresnel transform for each successive slice on a spatial light modulator by representing the real component of the complex amplitude of the Fresnel transform at a given location on the spatial light modulator on one pixel of the spatial light modulator at that location and representing the corresponding imaginary component of the complex amplitude of the Fresnel transform at that location on a second pixel of the spatial light modulator at that location;

illuminating the spatial light modulator so as to project a light distribution corresponding to the Fresnel transforms to a desired point in space; and

repeating the display and illumination of each Fresnel transform on the spatial light modulator.

According to an eighth aspect of the present invention, there is provided an apparatus for holographically generating a three dimensional light distribution, comprising:

a spatial light modulator in which pairs of pixels of the spatial light modulator are associated with each other;

means for displaying on a first pixel of a pair of associated pixels of the spatial light modulator, the real component of the complex amplitude of a light distribution to be displayed at that location on the spatial light modulator and for displaying on the second pixel of the pixel pair the corresponding imaginary component of the complex amplitude of the light distribution at that location;

means for dividing a desired light distribution into plural successive cross-sectional slices;

means for determining a Fresnel transform for each cross-sectional slice;

means for displaying the Fresnel transform for each successive slice on the spatial light modulator by representing the real component of the complex amplitude of the Fresnel transform at a given location on the spatial light modulator on one pixel of a pair of associated pixels of the spatial light modulator at that location and representing the corresponding imaginary component of the complex amplitude of the Fresnel transform at that location on the associated, second pixel of that pixel pair of the spatial light modulator;

means for illuminating the spatial light modulator so as to project a light distribution corresponding to the Fresnel transforms to a desired point in space; and

means for repeating the display of each Fresnel transform on the spatial light modulator.

As discussed, the three dimensional light distribution that is created could be intended to produce an image for viewing, or could be for use as optical "tweezers" or "traps" (in which case, it may, e.g., be in the form of an array of multiple spots or beams, or a "bottle-neck").

The repetition rate of the display should be appropriate for the intended use of the projected "light distribution". Thus, for example, in the case of an image to be viewed, it should be sufficiently frequent to achieve persistence of vision effects. In other cases, as discussed above, other repetition rates may be suitable and preferred. In general, the repetition rate should be such as to achieve the desired "level" of persistence for the light distribution.

As will be appreciated by those skilled in the art, all of the above aspects and embodiments of the invention can include any one or more or all of the preferred and optional features of the invention described herein, as appropriate.

The methods in accordance with the present invention may be implemented at least partially using software e.g. computer programs. It will thus be seen that when viewed from further aspects the present invention provides computer software specifically adapted to carry out the methods hereinabove described when installed on data processing means, and a computer program element comprising computer software code portions for performing the methods hereinabove described when the program element is run on data processing means. The invention also extends to a computer software carrier comprising such software which when used to operate a holographic display system comprising data processing means causes in conjunction with said data processing means said system to carry out the steps of the method of the present invention. Such a computer software carrier could be a physical storage medium such as a ROM chip, CD ROM or disk, or could be a signal such as an electronic signal over wires, an optical signal or a radio signal such as to a satellite or the like.

It will further be appreciated that not all steps of the method of the invention need be carried out by computer software and thus from a further broad aspect the present invention provides computer software and such software installed on a computer software carrier for carrying out at least one of the steps of the methods set out hereinabove.

The present invention may accordingly suitably be embodied as a computer program product for use with a computer system. Such an implementation may comprise a series of computer readable instructions either fixed on a tangible medium, such as a computer readable medium, for example, diskette, CD-ROM, ROM, or hard disk, or transmittable to a computer system, via a modem or other interface device, over either a tangible medium, including but not limited to optical or analogue communications lines, or intangibly using wireless techniques, including but not limited to microwave, infrared or other transmission techniques. The series of computer readable instructions embodies all or part of the functionality previously described herein.

Those skilled in the art will appreciate that such computer readable instructions can be written in a number of programming languages for use with many computer architectures or operating systems. Further, such instructions may be stored using any memory technology, present or future, including but not limited to, semiconductor, magnetic, or optical, or transmitted using any communications technology, present or future, including but not limited to optical, infrared, or microwave. It is contemplated that such a computer program product may be distributed as a removable medium with accompanying printed or electronic documentation, for example, shrink-wrapped software, pre-loaded with a computer system, for example, on a system ROM or fixed disk, or distributed from a server or electronic bulletin board over a network, for example, the Internet or World Wide Web.

A number of preferred embodiments of the present invention will now be described by way of example only and with reference to the accompanying drawings, in which:

Figure 1 shows schematically a first embodiment of a three dimensional projection display system in accordance with the present invention;

Figure 2 shows schematically the operation of the spatial light modulator in the system of Figure 1; and

Figure 3 shows schematically a second embodiment of a three dimensional projection display system in accordance with the present invention.

Figure 1 shows a first embodiment of a 3D projection display system in accordance with the present invention. In this system, a holographic arrangement is used to produce a three dimensional real image of a CAD solid model displayed on a CAD workstation 1 in a scattering medium 2.

In order to reproduce the three dimensional image in the scattering medium 2, successive cross-sectional level slice images through the CAD solid model are displayed as appropriate holograms (as will be explained further below) on a liquid crystal spatial light modulator 3, which is illuminated with a coherent read-out beam to "read-out" the holograms as they are displayed.

The holograms can be and are "read-out" using conventional techniques. Thus, in this embodiment, the coherent read-out illumination is provided by a laser source in the form of a laser diode 4 having a wavelength of 500 to 600 nm. The laser light is passed through a beam expander 6 and reflected by a mirror 7 into a polarising beam splitter 8 which reflects the beam onto the spatial light modulator 3. The light (coherent illumination) reflected from the spatial light modulator 3 (which will accordingly have been modulated by the hologram being displayed on the spatial light modulator 3 and has a Gaussian beam profile) then returns through the polarising beam splitter 8 and passes through a Fourier transform lens system 5 which transforms and focusses the reflected illumination appropriately into the scattering medium 2 such that the corresponding cross-sectional image is reconstructed at the desired z-axis position (shown with dashed lines in Figure 1) within the scattering medium 2.

The scattering medium 2 is a translucent block for viewing the real image reconstruction and is in the form of an Agarose gel block. The scattering medium cell 2 is mounted on a piezo-electric transducer that can be activated to induce a small mechanical motion to the scattering medium 2. This helps to ameliorate speckle noise within each reconstructed cross-sectional slice of the image (since the slight mechanical movement of the scattering medium will tend to average-out the speckle over the short period during which the cross-sectional slice is reconstructed). Other techniques for reducing speckle contamination (and for producing a real image) could be used, if desired.

The spatial light modulator 3 is in the form of an analogue ferroelectric liquid crystal spatial light modulator which comprises an analogue silicon backplane which addresses a ferroelectric smectic A* liquid crystal layer. The spatial light modulator 3 is designed for high-speed addressing, and is capable of displaying up to 4000 frames per second. This frame rate allows, for example, display of 200 different holograms (cross-sectional layers) on the spatial light modulator to be fully up-dated 20 times a second, which would give adequate z-axis resolution at an up-date speed sufficient to give a fully three dimensional display. The spatial light modulator is, as is known in the art, arranged as an array of pixels (for example as an array of 512 x 512 pixels), each of which pixels can be addressed independently to accordingly modulate light incident on that particular pixel location.

The spatial light modulator 3 also has the capability to rotate the polarisation of a linear polarised addressing beam, and has the ability to control the polarisation by up to 8 bits of resolution and in a bi-polar manner (i.e. clockwise or anti-clockwise from the vertical polarisation of the addressing beam). Furthermore, any linearly polarised addressing beam reflected from the spatial light modulator 3 will have its horizontal polarisation component separated upon passing through a polarising beam splitter, thereby leaving a bi-polar linearly polarised beam. The effect of this is that by addressing the spatial light modulator 3 using laser light 4 that is reflected from the polarising beam splitter 8 and then, after reflection by the spatial light modulator 3, passed through the polarising beam splitter 8, it is effectively possible to provide 8 bits of encoding resolution at each pixel of the spatial light modulator 3.

A suitable such spatial light modulator is the Multi-Level/Analog Liquid Crystal Spatial Light Modulator having an analogue silicon backplane and filled with a ferroelectric liquid crystal (using a smectic C* or a smectic A* phase liquid crystal) produced by Boulder Nonlinear Systems, Inc., of LaFayette, Colorado, USA. This device is available in a number of resolutions, such as 128 by 128, 256 by 256, and 512 by 512 pixels.

To display an image of the CAD solid model on the CAD workstation 1 in the scattering medium 2, the CAD solid model is first divided into plural cross-sectional slices along a z-axis that points normal to the face of the spatial light modulator 3 by means of a level slice processor 9. This processor produces, in the present embodiment, level slice images at 512 x 512 pixel resolution.

A firmware 2-dimensional fast Fourier transform engine 10 is then used to determine the appropriate Fresnel transform holographic representation of each cross-sectional slice for display on the spatial light modulator 3, so that the system can reproduce the appropriate image in the scattering medium 2. In this embodiment, the Fourier transform engine 10 produces 512 x 512 pixel transforms at a frequency of 500 Hz.

Fresnel transforms (which correspond to a Fresnel diffraction integral) are used because they provide an appropriate two dimensional modulation pattern that corresponds to the three dimensional pattern that it is desired to display.

To calculate the Fresnel transform holograms representing each cross-sectional slice in the image the Fourier transform engine 10 applies an appropriate quadratic phase factor to the Fourier transform of the required cross-sectional intensity pattern.

The Fresnel holograms calculated by the fast Fourier transform engine 10 are then displayed on the spatial light modulator 3.

These Fresnel holograms to be displayed on the spatial light modulator are, as is known in the art, complex signals, i.e. they contain amplitude and phase information at each spatial location in the Fresnel plane. Accordingly, it is necessary to be able to represent this complex signal appropriately on the spatial light modulator 3. This is achieved, as discussed above, by using the Applicant's previously proposed technique for full complex modulation of a spatial light modulator in the Fourier plane. Further details of these techniques can be found in the Applicants' papers "Fully Complex Optical Modulation using an Analogue Ferroelectric Spatial Light Modulator", P.M. Birch, R.C.D. Young, D.M. Budgett, C.R. Chatwin, Optics Communications, Vol. 175, pp. 347-352, March 2000, and "Two pixel computer generated hologram using a zero twist nematic liquid crystal spatial light modulator", P.M. Birch, R.C.D. Young, D.M. Budgett, C.R. Chatwin, Optics Letters, Vol. 25, No. 14, pp. 1013-1015, 2000.

Thus, to achieve the necessary complex encoding on the spatial light modulator 3, the pixels of the spatial light modulator 3 are arranged in pairs as "macropixels", with one pixel of each pair being used to represent the (entire) real component of the complex wavefront (i.e. Fresnel transform) at that particular pixel location, and the second pixel of each pair being used to represent the (entire) imaginary component of the wavefront at that pixel location. In this way, only two pixels of the spatial light modulator 3 are needed to represent the fully complex wavefront at a given location on the spatial light modulator 3.

Furthermore, the imaginary component needs to be orthogonal to the real component, i.e. $\pi/2$ phase shifted from it. This phase shift between the two pixels of each pair is achieved by using a phase detour technique to effectively provide a relative $\pi/2$ phase lag between the two pixels of each pair. In effect, the spatial light modulator is tilted by an angle such that each pixel has a phase lag of $\pi/2$ relative to its immediately adjacent pixels (in practice this effect is achieved by reading the image on the spatial light modulator at a reconstruction angle corresponding to a relative $\pi/2$ phase lag between adjacent pixels). In this way, modulation of the imaginary component is achieved by imposing a $\pi/2$ phase difference relative to the pixel containing the corresponding real component.

This arrangement is illustrated in Figure 2, which shows a sequence of three macropixels of the spatial light modulator 3 and the appropriate reconstruction (viewing) direction 20. As can be seen from Figure 2, the pixels of the spatial light modulator 3 are arranged in pairs R1, I1, R2, I2, R3, I3, etc., with one pixel in each pair representing the real component and the second pixel in each pair being modulated with the appropriate imaginary component. The whole system is viewed at a reconstruction angle corresponding to a relative $\pi/2$ phase lag between the two pixels of each pair. In this way, the desired fully complex phasor at each location on the spatial light modulator can be achieved.

It should be noted that, as shown in Figure 2, with this technique the adjacent real axis pixels will in fact be π out of phase with each other (i.e. in Figure 2, R1 and R2 would be π out of phase with each other). This can lead to an undesirable secondary reconstruction in the output plane. To overcome this, as shown in Figure 2, the data on every second real and imaginary pixel pair is multiplied by -1 (which can be done due to the bipolar ability of the spatial light modulator 3).

As will be appreciated by those skilled in the art, implementation details, such as with regard to the size and location of the reconstructed 3-D image, etc., can be selected and determined by appropriate selection of the values used for the various parameters of the reconstruction system.

In the present embodiment, it is preferred for the pixels of the spatial light modulator to be "doubled up" in the direction that is orthogonal to the direction of a line joining the imaginary component pixel and real component pixel of each pixel pair (i.e. in a direction perpendicular to the plane of the paper in Figure 2), so as to form symmetrical "super-pixels", each comprising four normal pixels. This can be achieved by placing the same data on each pixel of a pair of contiguous pixels lying in a direction orthogonal to the direction of a line joining the real component pixel and the imaginary component pixel of the pixel pair. In other words, there would in effect be two identical real and imaginary component pixel pairs lying side-by-side. This ensures that the two sets of pixel pairs have the same aspect ratio, i.e. the "super-pixel" that includes both the real and imaginary components for that pixel location has the same width and height.

In an alternative arrangement for matching the aspect ratio of the pixel pairs, the spatial light modulator (i.e. its silicon backplane) could be constructed so that is individual pixels have an aspect ratio of two-to-one, such that two pixels side-by-side (i.e. a real component pixel and its corresponding imaginary component pixel) would have the same width as the pixel height.

To display the image, the Fresnel transform holograms determined by the fast Fourier transform engine 10 are appropriately two-pixel encoded and loaded onto the spatial light modulator 3 in the manner described above. The spatial light modulator is simultaneously illuminated with the coherent laser source 4, such that the modulated reflected coherent illumination will pass through the Fourier transform system 5 to be reconstructed in the scattering medium 2 to form the three-dimensional display. (The exact plane at which the image of a given cross-sectional slice is re-constructed will depend, as is known in the art, on the quadratic term incorporated into the Fresnel transform for that particular cross-sectional slice.)

This process is repeated for all the cross-sections of the CAD solid model 1 that it is desired to display, with the display of the cross-sections being time multiplexed and repeated in an appropriate manner to allow persistence of vision to give the illusion of a full three dimensional image in the scattering medium 2.

In this way, a fully three dimensional display of the solid model on the CAD workstation 1 at the orientation corresponding to that current on the workstation 1 display can be generated in (near) real-time. This facilitates, for example, the three dimensional display in the scattering medium 2 being interactively and dynamically updated and changed as a user moves and reorients the CAD solid model on the workstation display 1.

Although the system in Figure 1 has been shown with the image being displayed as a real image in the scattering medium 2, it would also be possible for the image to be viewed as a virtual image by placing the eye looking into the spatial light modulator 3 (with appropriate guarding from the unfracted light from the spatial light modulator).

It should also be noted that although the present embodiment has been described in the context of displaying a single cross-sectional slice on the spatial light modulator 3 at any one time, since, as discussed above, the spatial light modulator 3 in fact has a dynamic range of up to 8 bits, it would be possible to multiplex holograms representing different cross-sectional slices onto the spatial light modulator 3 simultaneously. In this way, plural cross-sectional slices could be superimposed onto the spatial light modulator 3 and accordingly displayed in the scattering medium 2 (or otherwise) simultaneously. This would facilitate, e.g., greater flexibility between the dynamic range requirements of the spatial light modulator 3, the resolution in the z-axis, and the required frame rate to induce persistence of vision.

It would also be possible to use the 3D protection display system of Figure 1 to display a colour reconstruction. In one such arrangement, each cross-sectional slice of the CAD solid model could be further divided into red, green and blue colour segments, with the spatial light modulator 3 then being illuminated with the appropriate wavelength (red, green or blue) during display on the spatial light modulator 3 of the corresponding colour segment for the particular cross-sectional slice being reconstructed. In this way, a colour image in the scattering medium 2 can be built-up by displaying in sufficiently quick succession the colour "segments" for each cross-sectional slice whilst illuminating the spatial light modulator 3 with the appropriate colour of light.

In an alternative colour display arrangement, three separate spatial light modulators each arranged as shown in Figure 1 could be used, with each spatial light modulator being arranged to display one of the three colour channels (and accordingly being addressed by a laser of corresponding wavelength). The modulated wavefronts from each spatial light modulator could then be combined by dichroic optics into a single multispectral beam which would subsequently be passed through an achromatic Fourier lens system to generate the holographic reconstruction.

In such colour display arrangements, any appropriate adjustment of the phase retardance of the spatial light modulators to compensate for the wavelength shifts for the three colours should be made. This could be done, for example, by prior calibration of the spatial light modulators dispersion characteristics.

Figure 3 shows schematically a second preferred embodiment of a 3D projection display system in accordance with the present invention. This embodiment will, in particular, allow the image to be read out using a white light source.

The system shown in Figure 3 again includes a CAD workstation 1 on which a CAD solid model can be displayed, a level slice processor 9, a fast Fourier transform engine 10, a spatial light modulator 3, and a laser light source 4, beam expander 6, polarising beam splitter 8 and Fourier transform lens system 5 for illuminating the spatial light modulator 3 and reconstructing the appropriate image.

The system shown in Figure 3 further includes a volume holographic medium 30, a white light source 31, a collimating lens 32 for the white light source, a beam splitter 33 for directing the white light source light and the laser light appropriately and a beam scanning device 34. The holographic medium 30 can comprise any suitable such medium, such as a photo-refractive crystal such as Bismuth Silicon Oxide or Lithium Niobate. It is preferably repeatedly (and dynamically) recordable and erasable, preferably many times.

As shown in Figure 3, the system of this embodiment is arranged such that the three dimensional images of the cross-sectional slices corresponding to the holograms displayed on the spatial light modulator 3 are projected "into" the volume holographic medium 30. This allows the projected images to be recorded in the volume holographic medium 30.

The projected images are recorded in the holographic medium 30 by simultaneously illuminating the volume holographic medium 30 with the coherent light from the laser source 4. As successive cross-sectional slices are projected into the holographic medium 30, the angle of the recording reference beam is changed by a small amount between successive exposures by means of the beam scanning device 34. In this way, the multiple successive holograms are angle-multiplexed within the volume holographic medium 30.

This allows the storage capacity of the volume holographic medium 30 to used to record multiple successive holograms projected from the spatial light modulator 3, each corresponding to a cross-sectional slice through the image to be reconstructed, as superimposed angle multiplex volume holograms in the volume holographic medium 30.

The holograms recorded in the volume holographic medium 30 can then be reconstructed by scanning a collimated white light reference "read" beam (i.e. that is spatially coherent but temporally incoherent) from the white light source 31 through the same set of angles as the recording reference beam was scanned through, to reconstruct, for example, a corresponding real image in a scattering medium, or alternatively to allow an observer to view a virtual image by looking into the volume hologram.

An advantage of this arrangement is that because the three dimensional holographic display can be reconstructed using a temporally incoherent white light source, no speckle noise will be introduced into the reconstruction. This may therefore allow higher reconstruction qualities to be achieved.

As discussed above, the present invention in effect facilitates the generation of arbitrary three dimensional light distributions in a given volume of space. As well as the particular applications discussed above of using this technique to display three dimensional images, the technique can similarly be used to project three dimensional light distributions for other purposes, such as, for example, for optical trapping and manipulation applications.

For example, the present embodiments and invention could be used to generate in real-time under user control three dimensional spot arrays in which the individual elements can be individually controlled in three dimensions by a user, thereby facilitating fully interactive beam manipulations for use in, for example, optical manipulation of biological cells and sub-cellular components, and/or micro-manipulation in colloidal physics and nanofabrication of materials.

The present embodiments and invention could similarly be used to generate appropriate three dimensional light distributions to act as optical traps for cold atom research. For example, they could be used to provide light distributions shaped as bottle beams which could confine a cold atom condensate to a progressively narrower region towards the neck of the bottle. In such an application, the light distribution would not have to be continuously in place to maintain confinement and, for example, a 1000 Hz refresh rate would be adequate.

Where necessary, multiple spatial light modulators (such as in a similar manner to the colour display arrangement discussed above) could be used to generate the appropriate three dimensional light distribution at the desired repetition rate. Furthermore, as discussed above, multiple cross-sectional slices could be multiplexed into a single hologram for display on the spatial light modulator simultaneously, so that they are generated simultaneously. This could allow the production of an arbitrary three dimensional sheath of light to guide cold atoms.

As will be appreciated from the above, the present invention provides a technique for producing fully three dimensional displays. It also facilitates the interactive display and manipulation of the three dimensional display and, in preferred embodiments, the reconstruction of such displays using white light sources.

This is achieved, in the preferred embodiments of the present invention at least, by dividing a representation (such as a CAD model) of the object (image) to be displayed into plural cross-sectional slices, calculating a Fresnel transform of each slice, displaying the Fresnel transforms on a spatial light modulator, and then reconstructing the wavefront reflected or transmitted by the spatial light modulator to an image (the three-dimensional image that is viewed).

CLAIMS

1. A method of generating a three dimensional image of an object, comprising:

dividing a representation of an object to be imaged into plural successive cross-sectional slices;

determining a Fresnel transform for each slice;

displaying the Fresnel transform for each successive slice on a spatial light modulator by representing the real component of the complex amplitude of the Fresnel transform at a given location on the spatial light modulator on one pixel of the spatial light modulator at that location and representing the corresponding imaginary component of the complex amplitude of the Fresnel transform at that location on a second pixel of the spatial light modulator at that location;

illuminating the spatial light modulator such that the Fresnel transforms displayed on the spatial light modulator modulate the illuminating light beam; and

repeating the display and illumination of each Fresnel transform on the spatial light modulator sufficiently frequently so as to allow a three dimensional display of an image of the object through persistence of vision effects to be achieved.

2. The method of claim 1, comprising determining each Fresnel transform by applying an appropriate quadratic phase factor to the Fourier transform of the required cross-sectional intensity pattern.

3. The method of claim 1 or 2, comprising using a phase detour technique to achieve a $\pi/2$ relative phase shift between the real and imaginary components as seen from the image reconstruction.

4. The method of claim 1, 2, or 3, comprising multiplying the data on every second real and imaginary pixel pair by -1.

5. The method of claim 1, 2, 3 or 4, comprising arranging the system so as to ensure that the displayed Fresnel transforms are displayed such that at each pixel location on the spatial light modulator, the image displayed has a one-to-one aspect ratio.

6. The method of any one of the preceding claims, comprising displaying more than one cross-sectional slice on the spatial light modulator at the same time.

7. The method of any one of the preceding claims, wherein the display can be controlled and manipulated by a user.

8. A method of generating a three dimensional image of a CAD solid model, comprising:

dividing a CAD solid model into plural successive cross-sectional slices;

determining a Fresnel transform for each cross-sectional slice;

displaying the Fresnel transform for each successive slice on a spatial light modulator;

illuminating the spatial light modulator such that the Fresnel transforms displayed on the spatial light modulator modulate the illuminating light beam; and

repeating the display and illumination of each Fresnel transform on the spatial light modulator sufficiently frequently so as to allow a three dimensional display of the CAD solid model through persistence of vision effects to be achieved.

9. The method of any one of the preceding claims, wherein the system is arranged to produce a colour three dimensional display.

10. The method of any one of the preceding claims, further comprising recording the holograms generated using the spatial light modulator into a volume holographic medium.

11. A method of recording in a volume holographic medium a hologram for generating a three dimensional image of an object, comprising:

dividing a representation of an object to be imaged into plural successive cross-sectional slices;

determining a near field hologram for each slice;

displaying the near field hologram for each successive slice on a spatial light modulator;

illuminating the spatial light modulator such that the displayed near field holograms modulate the illuminating light beam;

reconstructing the corresponding image in the volume holographic medium; and

simultaneously illuminating the volume holographic medium with a coherent recording reference beam so as to record the projected reconstructed images in the volume holographic medium.

12. A method of generating a three dimensional light distribution, comprising:

dividing a desired light distribution into plural successive cross-sectional slices;

determining a Fresnel transform for each cross-sectional slice;

displaying the Fresnel transform for each successive slice on a spatial light modulator by representing the real component of the complex amplitude of the Fresnel transform at a given location on the spatial light modulator on one pixel of the spatial light modulator at that location and representing the corresponding imaginary component of the complex amplitude of the Fresnel transform at that location on a second pixel of the spatial light modulator at that location;

illuminating the spatial light modulator so as to project a light distribution corresponding to the Fresnel transforms to a desired point in space; and

repeating the display and illumination of each Fresnel transform on the spatial light modulator.

13. An apparatus for holographically displaying a three dimensional image of an object, comprising:

a spatial light modulator in which pairs of pixels of the spatial light modulator are associated with each other;

means for displaying on a first pixel of a pair of associated pixels of the spatial light modulator, the real component of the complex amplitude of an optical wavefront to be displayed at that location on the spatial light modulator and for displaying on the second pixel of the pixel pair the corresponding imaginary component of the complex amplitude of the optical wavefront at that location;

means for dividing a representation of an object to be imaged into plural successive cross-sectional slices;

means for determining a Fresnel transform for each slice;

means for displaying the Fresnel transform for each successive slice on the spatial light modulator by representing the real component of the complex amplitude of the Fresnel transform at each given location on the spatial light modulator on the first pixel of the pair of associated pixels of the spatial light modulator at that location and by representing the corresponding imaginary component of the complex amplitude of the Fresnel transform on the associated, second pixel of that pixel pair of the spatial light modulator;

means for illuminating the spatial light modulator such the Fresnel transforms displayed on the spatial light modulator modulate the illuminating light beam; and

means for repeating the display and illumination of each Fresnel transform on the spatial light modulator sufficiently frequently so as to allow a three dimensional image of the object to be achieved through persistence of vision effects.

14. The apparatus of claim 13, wherein the spatial light modulator includes a fast effect liquid crystal and is multi-level addressable.

15. The apparatus of claim 13 or 14, wherein the means for determining a Fresnel transform for each slice comprises means for determining each Fresnel transform by applying an appropriate quadratic phase factor to the Fourier transform of the required cross-sectional intensity pattern.

16. The apparatus of claim 13, 14 or 15, comprising means for multiplying the data on every second real and imaginary pixel pair by -1.

17. The apparatus of claim 13, 14, 15, 16, wherein the apparatus is arranged so as to ensure that the displayed Fresnel transforms are displayed such that at each pixel location on the spatial light modulator, the image displayed has a one-to-one aspect ratio.

18. The apparatus of any one of claims 13 to 17, comprising means for allowing a user to control and manipulate the display.

19. An apparatus for holographically displaying a three dimensional image of a CAD solid model, comprising:

a spatial light modulator;

means for dividing a CAD solid model to be displayed into plural successive cross-sectional slices;

means for determining a Fresnel transform for each cross-sectional slice;

means for displaying the Fresnel transform for each successive slice on the spatial light modulator;

means for illuminating the spatial light modulator such that the Fresnel transforms displayed on the spatial light modulator modulate the illuminating light beam; and

means for repeating the display and illumination of each Fresnel transform on the spatial light modulator sufficiently frequently so as to allow a three dimensional image of the CAD model to be achieved through persistence of vision effects.

20. The apparatus of any one of claims 13 to 19, wherein the apparatus is arranged to produce a colour three dimensional display.

21. The apparatus of any one of claims 13 to 20, further comprising means for recording the holograms generated using the spatial light modulator into a volume holographic medium.

22. An apparatus for recording in a volume holographic medium a hologram for generating a three dimensional image of an object, comprising:

means for dividing a representation of an object to be imaged into plural successive cross-sectional slices;

means for determining a near field hologram for each slice;

means for displaying the near field hologram for each successive slice on a spatial light modulator;

means for illuminating the spatial light modulator such that the displayed near field holograms modulate the illuminating light beam;

means for reconstructing the corresponding image in the volume holographic medium; and

means for simultaneously illuminating the volume holographic medium with a coherent recording reference beam so as to record the projected reconstructed images in the volume holographic medium.

23. An apparatus for holographically generating a three dimensional light distribution, comprising:

a spatial light modulator in which pairs of pixels of the spatial light modulator are associated with each other;

means for displaying on a first pixel of a pair of associated pixels of the spatial light modulator, the real component of the complex amplitude of a light distribution to be displayed at that location on the spatial light modulator and for displaying on the second pixel of the pixel pair the corresponding imaginary component of the complex amplitude of the light distribution at that location;

means for dividing a desired light distribution into plural successive cross-sectional slices;

means for determining a Fresnel transform for each cross-sectional slice;

means for displaying the Fresnel transform for each successive slice on the spatial light modulator by representing the real component of the complex amplitude of the Fresnel transform at a given location on the spatial light modulator on one pixel of a pair of associated pixels of the spatial light modulator at that location and representing the corresponding imaginary component of the complex amplitude of the Fresnel transform at that location on the associated, second pixel of that pixel pair of the spatial light modulator;

means for illuminating the spatial light modulator so as to project a light distribution corresponding to the Fresnel transforms to a desired point in space; and

means for repeating the display of each Fresnel transform on the spatial light modulator.

24. A volume holographic medium storing a hologram that has been recorded using the method of claim 10 or 11, or the apparatus of claim 21 or 22.

25. The use of the method of any one of claims 1 to 12 or of the apparatus of any one of claims 13 to 23 to generate multiple optical beams.

26. The use of the method of any one of claims 1 to 12 or of the apparatus of any one of claims 13 to 23 to produce a cold atom confinement trap.

27. A computer program element comprising computer software code portions for performing the method of any one of claims 1 to 12 when the program element is run on data processing means.

28. A method of generating a three dimensional image substantially as hereinbefore described with reference to any one of the accompanying drawings.

29. A method of recording a hologram for generating a three dimensional image substantially as hereinbefore described with reference to any one of the accompanying drawings.

30. A method of generating a three dimensional light distribution substantially as hereinbefore described with reference to any one of the accompanying drawings.

31. An apparatus for holographically displaying a three dimensional image substantially as hereinbefore described with reference to any one of the accompanying drawings.

32. An apparatus for recording a hologram for generating a three dimensional image substantially as hereinbefore described with reference to any one of the accompanying drawings.

33. An apparatus for holographically generating a three dimensional light distribution substantially as hereinbefore described with reference to any one of the accompanying drawings.

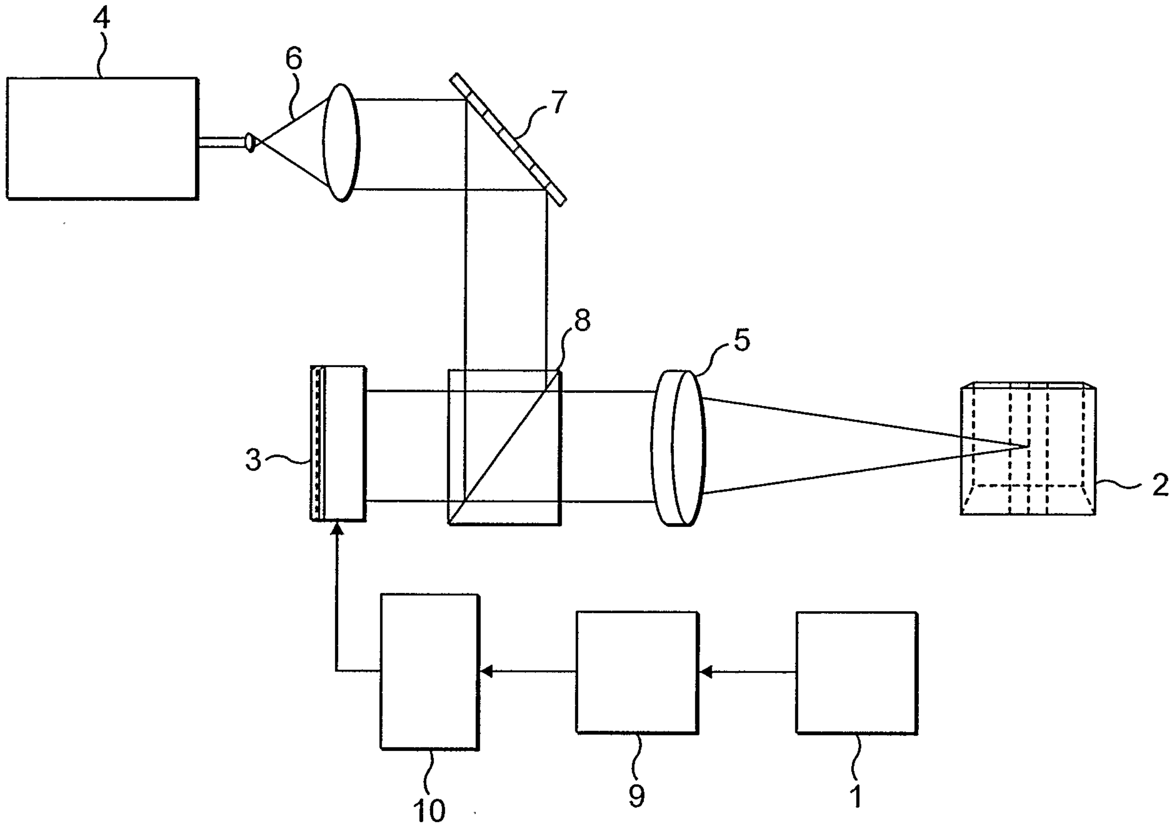

FIG. 1

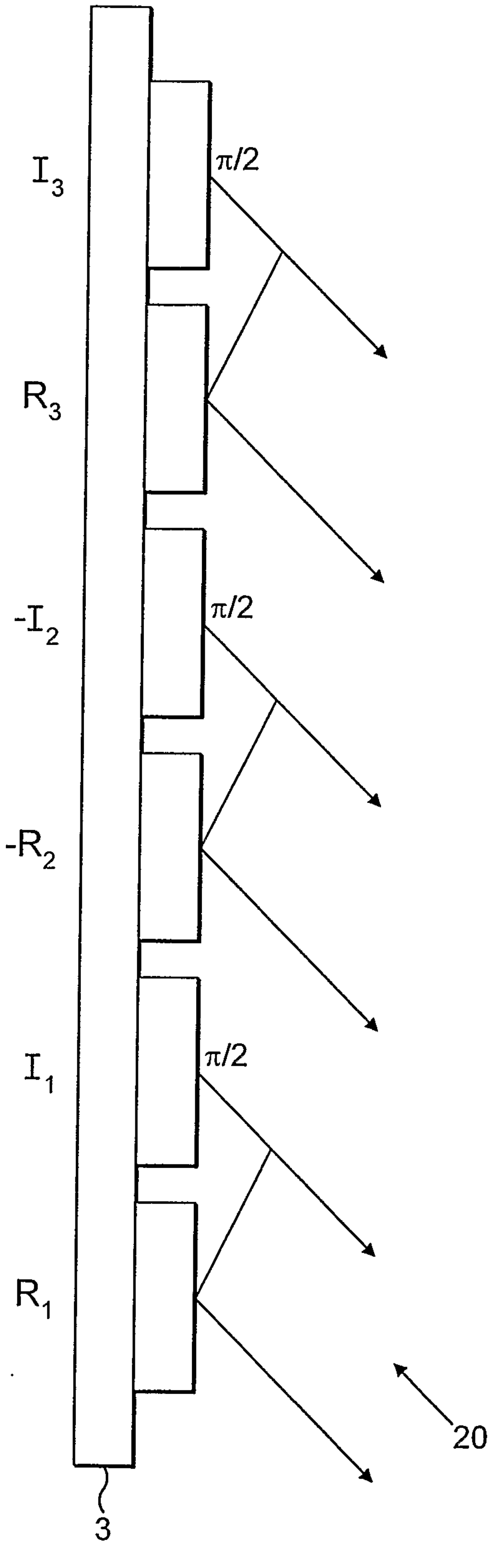

FIG. 2

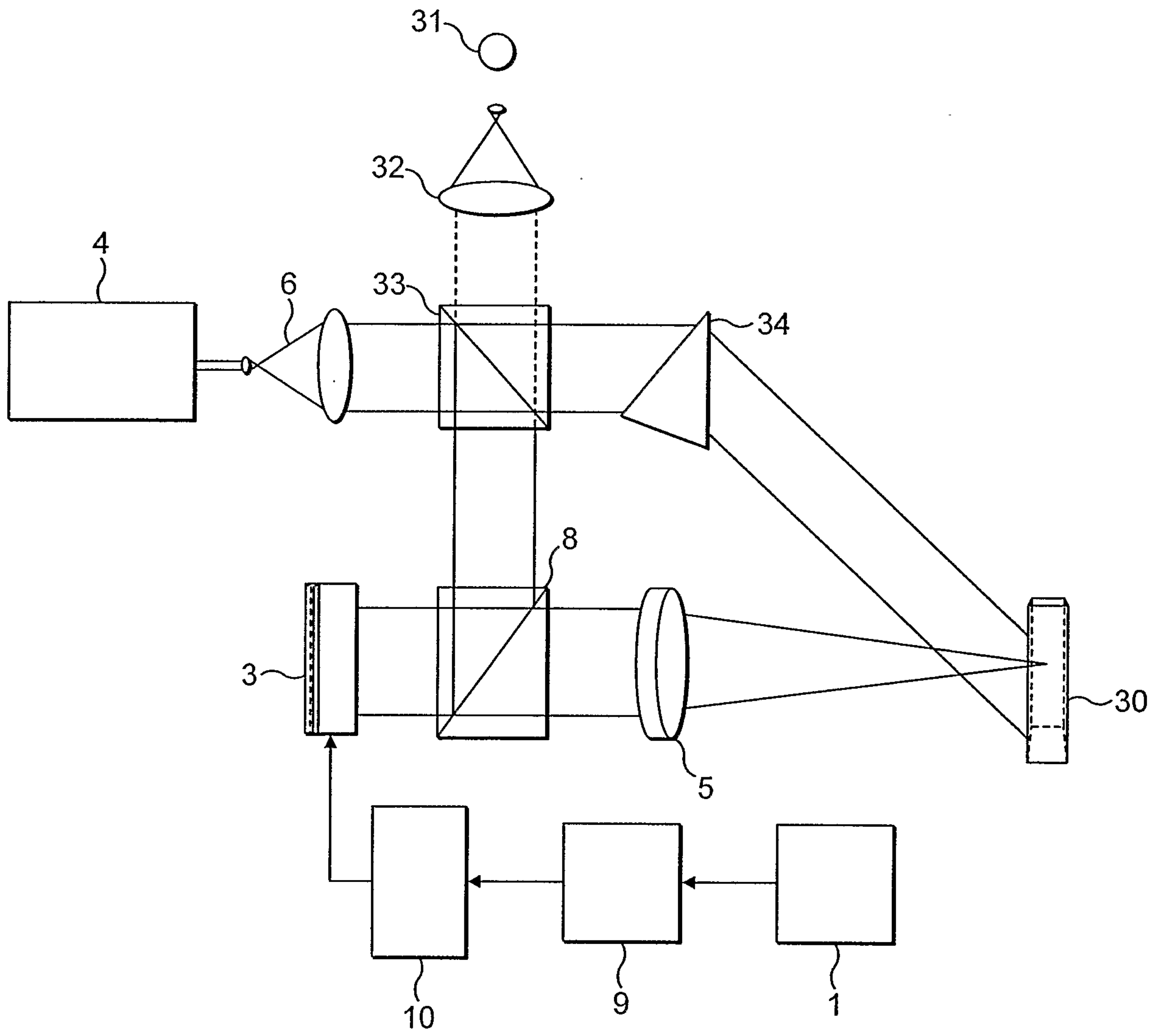

FIG. 3