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System and method for user interaction with a volumetric display

Field of the invention

The present invention relates to inputting data into a system including for a volumetric display apparatus, by which is meant an apparatus which is
5 capable of generating a three-dimensional visual image within a three-dimensional display space.

Background of Invention

With the advancement of technology, volumetric displays similar to the
10 "floating 3D display" shown in *Star Wars* have, become reality. This kind of new display apparatus generates true 3D volumetric images by illuminating points in a 3D "display space" rather than merely simulating the perception of viewing such points. Volumetric displays are thus able to provide all the depth cues humans require. As a result, this approach lets the viewers use their
15 natural physiological mechanisms for depth perception to gain a richer understanding of the virtual 3D scene. Furthermore, the users can view the display from almost any direction and multiple individuals can view it simultaneously.

20 Formerly, interaction with 3D data (e.g. CAD models) has been a great challenge for the designers and users, because current displays are limited to 2D. Volumetric displays not only provide a possible solution to this problem, but also opportunities for a totally new kind of interface between man and machine by a vivid copy of the real 3D world. However, most volumetric
25 displays are within in an enclosed space, due to their operational principles.

For example, reference [1] describes two promising volumetric display systems: a swept volume display system and a multiple-planar-screen display

system. The swept volume display system uses a high-definition projector or an array of lasers to bounce images off a screen that rotates within a transparent globe sufficiently fast that the human eye perceives only a 3-D image floating in the space. The multiple-planar-screen display system is an
5 entirely solid-state design that uses a projector behind a stack of multiple liquid-crystal screens to create one solid image from a rapidly projected series of images.

The working principle of both kinds of systems forbids the user's direct
10 interaction (physical presence) with the displayed data and normally the display space and the "user space" are separated by a transparent surface. This is a challenge for designing a user-friendly interaction mechanism between the viewer and the display.

15 Various methods exist, but all of them utilize a mapping between the user input in the "user space" and the system input in the "display space". This kind of method is not intuitive and requires an expensive tracking system to track the user's movement in the real 3D space. The mapping may also need calibration and re-calibrations.

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In references [2] and [3] several ways were proposed to realize interaction with a volumetric display system in a user-friendly manner. Mainly they use certain virtual mappings to correlate coordinates in a 2D/3D user input space with coordinates in the 3D display space. Specifically, reference [2] describes
25 two methods of special interest: (1) using a user's finger to touch the non-planar enclosure of the volumetric display apparatus, and mapping the 2D position on the enclosure into the 3D display space by a ray-casting method; and (2) using a digital stylus to specify both a 2D coordinate on the non-planar surface and to specify tilt information to enhance the ray-casting pointer input
30 model.

Unfortunately, both these methods have following limitations/disadvantages:

1) the requirement for a transparent digitization tablet as the enclosure (such tablets are currently unavailable); 2) the requirement for sensors or tracking method to get the pointing direction; 3) the mapping between the user space and the display space needs to be calibrated or pre-defined; and 4) the lack of the solution to specify an arbitrary point along the pointing direction (ray-casting vector).

Reference [4] proposes a manipulating device having a physical end and a virtual end (in the display space). The mapping between the physical end and the virtual end is fixed. Thus by tracking the position and orientation of the physical end, the corresponding position and orientation of the virtual end can be determined. This method has the disadvantages that: 1) a tracking system is needed to track the movement of the physical end in the user space; 2) the accuracy of the mapping depends on the tracking system performance; and 3) the mapping might not be intuitive (for example, the orientation of the virtual end is not necessarily aligned with the orientation of the physical end) and may cause confusion to the user.

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Reference [5] reviews a number of types of volumetric display apparatus, including (in addition to the ones mentioned above) volumetric display apparatus of a "static volume" type (in which a three-dimensional volume is coaxed to emit light, for example when doped glass is excited by intersecting infrared beams), "holograms and holographic stereogram"-type display apparatus, and "highly-multiview 3D displays".

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Summary of the Invention

The present invention aims to provide new and useful techniques and apparatus for interacting with a volumetric display.

Preferred embodiments of the invention may make it possible to interact with
5 the display in a more direct and natural way using a pointing device.

In general terms, the present invention proposes that a user manipulates a pointing device which emits an EM wave as a ray which physically penetrates into the display space defined by a volumetric display apparatus. Sensors embedded in the display apparatus are used to detect the ray, and so
10 determine the orientation of the ray in the coordinate system of display space.

In one form, the EM wave is a ray of (e.g. visible) light generated by an (e.g. visible) laser in the pointing device.

The volumetric display apparatus may, for example, be one of the kind having a rotational projection surface, or of the kind having multiple LCD display
15 layers. In either case, the sensors may be placed on the display surfaces. For example, the sensors may be positioned at known locations on the rotational single surface in a swept volume display system or on some (or normally all) of the multiple liquid crystal screens in a multiple-planar-screen display system. Each of the sensors may be associated with a respective region of
20 the display space, or of the surface on which it is mounted, such that the together the regions span an area or volume in the display space.

Optionally, the pointing device allows the user to specify a distance along the pointing direction of the pointing device using a (e.g. mechanical) data entry device on the pointing device. The volumetric display apparatus may display a
25 point at this specified distance along the pointing direction. In this case, using both the user's input on the pointing device and visual feedback using the

volumetric display apparatus, a 3D position along the pointing vector can be selected.

Furthermore, by combining these two kinds of information in one or more further steps in which the user makes selections of directions or distances, all
5 the six DOF (degree of freedom) in 3D space can be determined. Based on this information, more complex user interaction models with the 3D data can be derived.

Thus, in contrast to the prior art systems described above, certain embodiments of the present system have the advantages of: 1) intuitive
10 physical interaction between the user's action and the display space; 2) direct coordinate input (the input is directly overlapped on the displayed data) without the need for any mapping; and 3) the ability to specify an arbitrary point with the display region along the pointing direction.

The invention may be expressed as a volumetric display system comprising a
15 volumetric display apparatus, a pointing device and a (typically) separate processor, which may be a PC or other computing device. The invention may alternatively be expressed as a method for entering data into such a volumetric display system.

Brief Description of The Figures

20 Preferred features of the invention will now be described, for the sake of illustration only, with reference to the following figures in which:

Fig. 1 illustrates a volumetric display system which is a first embodiment of the invention;

Fig. 2 illustrates the interaction between an EM wave and a projection
25 screen in the first embodiment;

Fig. 3 is a flow diagram of the process used to determine a line equation in the first embodiment;

Fig. 4 illustrates the trace of the interaction between the EM wave and the projection screen in the first embodiment;

Fig. 5 is a flow diagram of a process used to specify a point along a pointing direction in the first embodiment;

5 Fig. 6 illustrates a volumetric display system which is a second embodiment of the invention;

Fig. 7, which is composed of Figs. 7(a) and 7(b), shows projections onto bottom and side planes for a trace analysis in an enhanced version of the system of Fig. 1; and

10 Fig. 8 illustrates in perspective view the fitted 3-D line in the enhancement of Fig. 7.

Detailed Description of the embodiments

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Referring firstly to Fig. 1, a schematic view of a volumetric display system which is first embodiment of the invention is shown. It includes a volumetric display apparatus having a transparent enclosure 1 mounted on a base 2. The base 2 further supports a projection surface 3 and contains a mechanism
20 for rotation the projection surface 3 about the vertical axis OP. The volumetric display apparatus further includes a projector (not shown) for projecting images onto the projection surface 3. The volumetric display system further comprises a PC 4 (or other computing system) to transmit control signals encoding 3-D data to the volumetric display apparatus along signal path 5.
25 These control signals control the operation of the projector.

All these features of the volumetric display system are in common with the swept volume display system of reference [1] described above. However, in contrast to the known system, in the embodiment of Fig. 1 the user interacts
30 with the display system using a pointing device 6 which emits an EM wave 7

as a ray that can penetrate the surface of the transparent enclosure 1 of the display system and reach the rotational projection surface. Although the pointing device is illustrated as elongate in Fig. 1 with the ray along its long axis, this need not be the case; the pointing device points by emitting the ray 7, rather than by virtue of its shape. The display device 6 is typically hand-held.

- A plurality of sensors for detecting the EM wave 7 are provided on the rotational projection surface at respective pre-known locations on the surface.
- 10 These EM sensors can sense the EM wave 7 transmitted from the pointing device 6. For example, the pointing device 6 may be a laser pointer generating a visible laser ray 6, and the EM sensors may be respective photo diodes.
- 15 The signals from the EM sensors are transmitted from the display system to the PC 4 along signal path 8, and the PC 4 combines the sensor information with timing information of the display system indicating the rotational position of the rotational projection surface 3 at the time that the EM wave was detected. Using these two sets of data, the PC 4 can determine the 3D
- 20 pointing vector in the display space (i.e. the trajectory of the ray 7).

The pointing device 6 is preferably provided with one or more data input devices (e.g. buttons and/or rollers). The user is able to manipulate these devices to enter data, which is transmitted to the PC 4 along a data path 9 (which may be wireless). By combining this data with the 3D pointing vector, the PC is able to determine a specific point along the pointing direction. In other words, the user can select such a point within the display volume.

The calculation of incoming direction (i.e. pointing direction set by the user) will now be discussed with reference to Figs. 2, and the flow diagram of Figs.

3 showing the processes for estimating the 3D pointing direction. For simplicity of discussion, let us assume that the rotational projection surface 3 is planar (it is straightforward to extend the discussion to other kinds of projection surfaces, e.g. helical or double helical surfaces). Furthermore, again for simplicity of discussion, it is assumed that the rotational projection surface 3 is rectangular in shape (not substantially semi-circular as shown in Fig. 1), but this discussion can straightforwardly be extended to projection surfaces of arbitrary shape.

10 When the rotational projection surface 3 makes one rotation around the central axis OP, the EM wave will intersect with the projection plane 3 at a series of different locations. There are always two intersection points on the edge of the projection surface 3 which correspond to the first and last intersection of the surface 3 with the EM wave in one rotation. These are denoted by P_1 and P_3 in Fig. 2. If EM sensors are placed along the edge of the projection surface 3 (they only need be provided on one side), the intersection times and the positions P_1 and P_3 along the edge of the projection surface can be obtained. The sensors may, for example, be laser photo diodes with nanosecond response, of the kind available in the market; in this case they are fast enough to operate when the surface 3 rotates at the common rotational speed of 25 rotations per second.

In step 10 of Fig. 3, the PC receives and collects the data discussed above: the positions of the sensors which detected the EM wave and the times at which these signals were received.

Given this data, it is straightforward to obtain the two intersection points P_1 and P_3 in a cylindrical coordinate system as $(R, \omega t_1, h_1)$ and $(R, \omega t_3, h_3)$, where R is the half-width of the projection surface, ω is the angular rotational speed of the projection surface, t_1 and t_3 are the time instances that EM waves are

detected at P_1 and P_3 respectively, and h_1 and h_3 are the heights of the two intersection points respectively.

Using two points' coordinates, instep 20, the PC uses this data to obtain the equation of the 3D line segment equation including the points P_1 and P_3 . Firstly, the coordinates can be transformed into Cartesian coordinates (with origin at O and z-axis coincides with that of the cylinder coordinate system) as Eqns. (1) and (2) respectively:

$$x_1 = R \cos(\omega t_1), \quad y_1 = R \sin(\omega t_1) \quad \text{and} \quad z_1 = h_1 \quad (1)$$

$$x_3 = R \cos(\omega t_3), \quad y_3 = R \sin(\omega t_3) \quad \text{and} \quad z_3 = h_3 \quad (2)$$

Then the line segment in the 3D space can be formulated as Eqn. (3).

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} = \begin{pmatrix} x_1 \\ y_1 \\ z_1 \end{pmatrix} + k \begin{pmatrix} x_3 - x_1 \\ y_3 - y_1 \\ z_3 - z_1 \end{pmatrix}, \quad \text{with } 0 \leq k \leq 1 \quad (3)$$

This 3D line equation is the output of step 20.

Note that there are other cases for how the intersection may happen. For example, one intersection point may be on the top edge of the surface 3 while and the other one is on the side edge. Also the projection surface 3 might not be a rectangle, but a circular plate; or it might not even be planar, but a 3D shape, such as a helical or double-helical shape. However, the process to get the 3D line equation is sufficiently similar to that described here that a skilled reader will be able to obtain it without difficulty.

It is also interesting to examine the whole locus of the intersection points within the projection plane, as illustrated in Fig. 4. It can be shown that the locus is a second order curve determined by the pointing direction of the EM

wave. It is possible to use information about the whole locus to improve the accuracy of pointing direction estimation. This can be done by distributing EM sensors all over the projection surface (again, only one side is needed) and using curve fitting methods (e.g. LMS) with information about the whole locus.

5 Not to distract the discussion, the details of this method are put in the Appendix.

Once the coordinates of the line segment P_1P_3 are known, a user is able to use one or more data input devices on the pointing device 6 (such as buttons and/or sliding bars) and a visual feedback from the display system, to select an arbitrary point within this line segment. This process is illustrated in the flow diagram of Fig. 5. The method takes as its input the 3D line segment equation of the pointing direction in the display space coordinate system obtained in the method of Fig. 3. In a first step (step 50) the volumetric display system generates an image of a point along the line segment. In step 60 the user presses buttons on the pointing device to "move" the selected point forward or backward along the 3D line segment. For example, two buttons or a sliding bar can be used to move one voxel forward or backward along the line (the line may be "locked" in the display when doing this operation) and the exact coordinate of current selection can be inferred and displayed as a feedback. In step 70, the user can press another button to "confirm" the selection.

Note that the processes of Figs. 3 and 5 may be also combined, or performed multiple times, to input more complex information. For example, in one selection process a user and display system may firstly select a certain voxel by specifying a point on a first line segment (by the methods of Figs. 3 and 5), and then selecting an axis of rotation by selecting another line segment through this voxel (by the method of Fig. 3). Thus, the full six DOF (degree of freedom) in a 3D space can be specified by the above method (3D coordinate

of a point plus the orientation of an axis). This basic information forms the base for more complex interaction with the volumetric display. A further possible example of the inputting of more complex information is for the user to use the method of Fig. 3 twice to select two non-parallel lines through a point selected by the method of Figs. 3 and 5, to define/select a plane that contains these two lines.

Turning to Fig. 6, a volumetric display system which is a second embodiment of the invention is illustrated. In this case, the volumetric display apparatus includes multiple planar liquid crystal screens 103 within a transparent enclosure 101. A PC (or other computing device) 104 transmits data encoding 3D image data along a signal path 105 to the volumetric display apparatus, which uses the data to control screens 103. This data controls the screens 103 in turn to become "diffusive" and to display a two-dimensional image; when one of the screens 103 is diffusive, the others are transparent. These features of the volumetric display system are the same as in the multiple-planar-screen display system of ref. [1] mentioned above.

However, in contrast to the known system, the user of the present embodiment interacts with the display system using a pointing device 106 which emits an EM wave 107 (e.g. laser ray) which can penetrate the surface of transparent enclosure 101 of the display system and reach the multiple screens 103. Since, during a display cycle, all but one of the screens are transparent at any time, the EM wave 107 intercepts each of the screens during the cycle. Each screen is provided with a plurality of EM wave sensors (not shown) provided (e.g. embedded) with a pre-defined distribution pattern. These sensors can sense the EM wave 107 transmitted from the pointing device 106. One example is the use of a laser pointer as the pointing device 107 and photo diodes as the sensors.

The output of the sensors is transmitted to the PC 104 along the signal path 105. The 3D coordinates of the intersection of the ray 107 with a screen are determined by the 2D coordinates on that screen of the sensor which detected the ray, and the z value (i.e. the position in the direction

5 perpendicular to the multiple planar screens) of that specific screen.

Combining this sensor information and timing information of the display system, the PC 104 can determine the 3D pointing vector in the display space by the process shown in Fig. 3. In principle, only the outputs from two sensors are required to obtain the 3D line equation. However, alternatively, the 3D line
10 equation can be estimated using LMS method using more than two of the intersection points.

Furthermore, the pointing device 106 is provided with data input devices such as buttons which generate data which is transmitted to the PC 104 along the
15 signal path 109. By a method as shown in Fig. 5, the user is able to select a point along the selected line, using display feedback in which the PC 104 modifies the image displayed by the screens 103 to show the selected point along the selected line segment. Note that interpolation may be applied to increase the z-direction resolution, as introduced in [1].

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Although only two embodiments of the invention have been described in detail, many variations are possible within the scope of the invention as will be clear to a skilled reader. For example, while the embodiments make use of two known volumetric display apparatus, other types of volumetric display
25 apparatus may be used in their place, for example the other types of volumetric display apparatus reviewed in [5].

References

The disclosure of the following references is incorporated herein in its entirety.

- [1] Alan Sullivan. 3-Deep: New Displays Render Images You Can Almost Reach Out and Touch. *IEEE Spectrum Magazine*, April 2005.
- 5 [2] US patent 6,753,847 B2.
- [3] Ravin Balakrishnan, George W. Fitzmaurice and Gordon Kurtenbach. User Interface for Volumetric Displays. *IEEE Computer Magazine*. March 2001.
- [4] US patent 6,765,566 B1.
- 10 [5] "Volumetric 3D displays and Application Infrastructure", Computer Magazine, p 37, August 2005, published by the IEEE Computer Society.

Appendix: A curve fitting method for 3D line estimation with the full locus detected.

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As described in the previous discussion, the 3D line estimation can be successfully done in the embodiment of Fig. 1 with the detection of only two boundary points as illustrated in Fig. 2. This method requires the EM sensors only to be deployed on the edge of the projection surface 3. However, there is
 20 another option of using more sensors to achieve better estimation results. The idea is to distribute sensors all over one side of the projection surface 3 and to detect the full locus of the intersection points of EM wave 7 and the surface 3.

To obtain the exact formulation for the locus, two projections of the 3D
 25 geometry are helpful in the analysis. One is the projection onto the bottom plane and the other is the projection on the plane formed by two vertical edges containing P_1 and P_3 respectively. These projections are shown respectively in Figs. 7(a) and 7(b).

Fig. 8 is a perspective view of the interaction of the EM wave 7 with the surface 3. The half-width of the projection plane R is pre-known. Angle α ($\alpha = \frac{\pi}{2} - \frac{\omega(t_3 - t_1)}{2}$) and the heights of two boundary intersections h_1, h_3 are uniquely determined by the position of the pointing line in the 3D space. As long as the pointing line is not changed, these values are fixed. Here the variable is θ , which is determined by the rotational mechanism and the instant time (with a constant angular velocity, this is a simple linear relationship). By geometric analysis, it can be obtained that:

$$x = \frac{\sin(\alpha)}{\sin(\alpha + \theta)} R \quad (4)$$

$$y = h_2 = h_1 + \frac{\sin(\theta)}{2 \cos(\alpha) \sin(\alpha + \theta)} (h_3 - h_1) \quad (5)$$

Using Eqns. (4) and (5), it is not difficult to find the equation for the locus in the Cartesian coordinate system as:

$$(h_3 - h_1)^2 x^2 - 4 \cos^2 \alpha R^2 (y - \frac{h_1 + h_3}{2})^2 = R^2 \sin^2 \alpha (h_3 - h_1)^2 \quad (6)$$

Eqn. (6) is a standard hyperbola curve, which is uniquely determined by the 3D position of the line. On the other hand, with the whole locus on the projection plane detected by sensors distributed on it, the 3D equation of the line can be determined.

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Denoting the detected points on the locus as: (x_i, y_i, t_i) , where (x_i, y_i) are the 2D coordinates on the projection surface 3 where the EM wave 7 is detected at time instance t_i , the objective is to use this information to estimate the 3D line equation. As shown above, the 2D coordinates will follow Eqn. (6). With a curve fitting technique, we can obtain the features of the hyperbola and

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consequently get estimation of α , $(h_3 - h_1)$ and $\frac{h_1 + h_3}{2}$. Also, by an interpolation method, we can find the trough point (x_0, y_0) and the corresponding time t_0 (refer to Fig. 4).

- 5 The estimated 3D line equation will then naturally be based on the center point of the line segment P as shown in Fig. 8 as:

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} = \begin{pmatrix} x_p \\ y_p \\ z_p \end{pmatrix} + k\vec{V} \quad (7)$$

- 10 where (x_p, y_p, z_p) is the 3D Cartesian coordinate of P and $\vec{V}$ is a direction vector in 3D space. They can be both extracted from the fitting results. Firstly, z_p is estimated by $\frac{h_1 + h_3}{2}$. x_p and y_p can be estimated as: $x_0 \cos(\omega t_0)$ and $x_0 \sin(\omega t_0)$ respectively. Thus, we have:

$$\begin{pmatrix} x_p \\ y_p \\ z_p \end{pmatrix} = \begin{pmatrix} x_0 \cos(\omega t_0) \\ x_0 \sin(\omega t_0) \\ \frac{h_3 + h_1}{2} \end{pmatrix} \quad (8)$$

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The estimation of $\vec{V}$ is based on the geometry analysis illustrated in Fig. 8. The z component of $\vec{V}$ is firstly estimated as $(h_3 - h_1)$. Then the x and y component can be estimated as $2R \cos \alpha \cos(\omega t_0 + \frac{\pi}{2})$ and

- 20 $2R \cos \alpha \sin(\omega t_0 + \frac{\pi}{2})$. This is because of the fact that $O'P'$ corresponds to the

time instance t_0 and is actually perpendicular to the plane $P_1P_3P_3'$. Thus $\vec{V}$ could be written as:

$$\vec{V} = \begin{pmatrix} 2R \cos \alpha \cos(\omega t_0 + \frac{\pi}{2}) \\ 2R \cos \alpha \sin(\omega t_0 + \frac{\pi}{2}) \\ h_3 - h_1 \end{pmatrix} \quad (9)$$

With Eqns. (7), (8) and (9), the 3D line equation is obtained using the curve
 5 fitting method and it is easy to see that k in Eqn. (7) should fall in the region
 of $[-\frac{1}{2}, \frac{1}{2}]$. This curve fitting method may result in a higher accuracy than
 using only the information of the two boundary points.

Claims

1. A volumetric display system comprising:
 - a display apparatus which generates a three-dimensional image by illuminating points within a three-dimensional display space;
 - 5 a pointing device for transmitting an EM wave as a ray which propagates through the display space;
 - a plurality of sensors within in display space for detecting the EM wave;
 - and
 - a processor for determining the trajectory of the EM wave from the
 - 10 output of the sensors.
2. A volumetric display system according to claim 1 in which the pointing device is a laser pointing device for generating said EM wave as a laser ray.
3. A volumetric display system according to claim 2 which the laser ray is a visible laser ray.
- 15 4. A volumetric display system according to any preceding claim in which the display system comprises a screen member including a screen, a drive mechanism for moving the screen member, and a projector for projecting an image onto the moving screen, the plurality of sensors comprising sensors mounted on the screen.
- 20 5. A volumetric display system according to claim 4 in which the screen member is arranged to rotate around an axis, the drive mechanism being arranged to rotate the screen member around the axis.

6. A volumetric display system according to claim 5 in which the plurality of sensors comprise a plurality of sensors provided on an edge of the screen member.
7. A volumetric display system according to any of claims 1 to 3 in which
5 the display apparatus comprises multiple display layers, the processor being arranged to generate and transmit to the volumetric display apparatus signals for controlling each of the display layers.
8. A volumetric display system according to claim 7 in which the plurality of sensors comprises a respective set of one or more sensors mounted on
10 each of the plurality of the display layers.
8. A volumetric display system according to any preceding claim in which the pointing device comprises a data entry device for registering a selection made by the user.
9. A volumetric display system according to claim 8 in which the
15 processor is arranged to receive data indicative of the user's interaction with the data entry device, and to determine a point on the trajectory of the EM wave based on the data.
10. A volumetric display system according to claim 9 in which the processor is arranged to transmit data indicative of said point to the display
20 apparatus for display by the display apparatus, whereby the user can view an image of the determined point while operating the data entry device.
11. A method of entering data into a volumetric display system comprising a display apparatus which generates a three-dimensional image by illuminating points within a three-dimensional display space; the method
25 comprising:

a user manipulating a pointing device for transmitting an EM wave as a ray which propagates through the display space;

two or more of a plurality of sensors within in display space detecting the EM wave; and

- 5 determining the trajectory of the EM wave from the output of the sensors.