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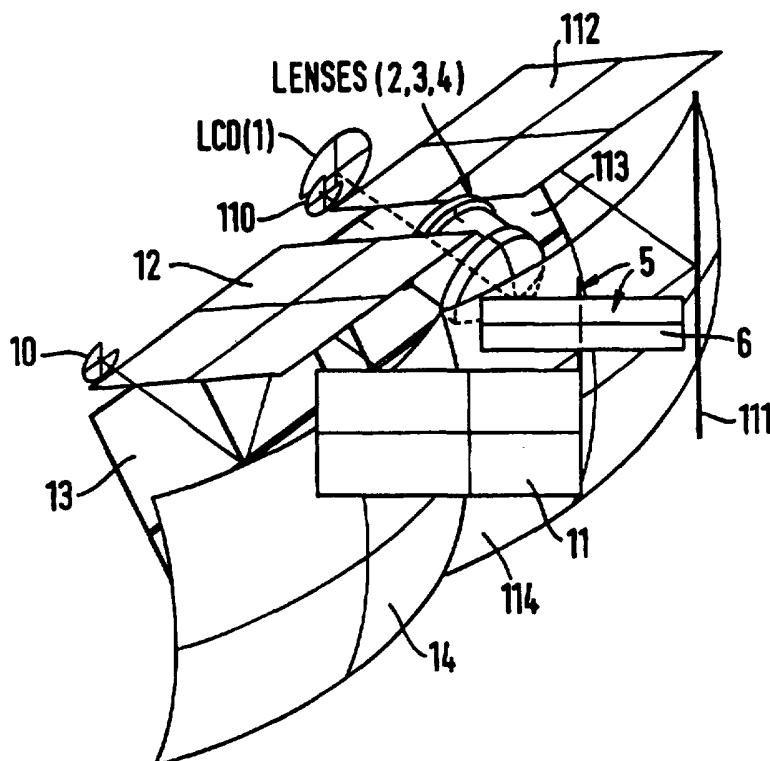
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(54) Title: HEAD MOUNTED DISPLAY OPTICS

(57) Abstract

A head mounted display for use in virtual reality applications and typically in the form of a slim visor is provided with binocular magnifying optics which permit the binocular viewing of an image displayed by a single miniature LCD video screen (501) magnified at infinity focus at left and right exit pupils (507). A vertically offset beamsplitter is provided having two elements (502, 508) being substantially mutually perpendicular planar semi-reflecting mirrors (in the illustrated embodiment) disposed respectively above or below the horizontal optical axis of the LCD (501). A single image viewed from the LCD (501) passes through the semi-reflecting mirrors (502, 508) to be reflected off a concave mirror (503). On reflection part of the image is reflected off element (502) and then by a right hand fold mirror (510) toward the right hand exit pupil (507). Another part of the image is similarly reflected off element (508) and left hand fold mirror (510) toward the left hand exit pupil (507). Magnification and/or optical correction of the images viewable at eyepoints (507) can be effected by a respective one of lens arrays (505). In other embodiments of the invention the disposition of optical elements permits the use of vertically offset beamsplitters which are wholly reflective, i.e. not semi-transmissive.



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"HEAD MOUNTED DISPLAY OPTICS"

This invention relates to an optics system suitable for a head mounted display apparatus generally and more particularly, but not exclusively, to a head mounted display apparatus comprising an optics system facilitating the binocular viewing of a single LCD screen image.

The development of head mounted display apparatus for viewing computer generated imagery has its roots in military aircraft weapons and flight simulation systems. Typically, such systems have required that a computer generated image is projected by means of an optical combiner on to a projection plane or surface overlapping the line of sight of a user, such as for example the curved visor of a helmet. One such example is illustrated in Figure 8 of US Patent Specification No. 5,050,966 in which a single cathode ray tube (CRT) mounted in the helmet rearwardly of the user's head feeds a mirrored optical path to a beamsplitting arrangement in the user's line of sight. The beamsplitter enables the user to view with both eyes the projected CRT image and the environment external of the helmet and in his line of sight. It will be understood that the aircraft helmet design can accommodate the described optical apparatus.

However, in many virtual reality applications a helmet of such size would inhibit the movement of a user in the real world when such movement is an integral part of most virtual reality experiences. In addition such designs are inherently complicated by the need to superimpose reasonable images projected from the CRT on to the user's view of the external environment. The design of combiner disclosed in that Specification is constrained by the requirement that the user should be able to view the external environment without eyestrain. As a consequence of this requirement, the design of the associated optics must provide the right performance after allowing for the combiner configuration. Virtual reality applications generally require the widest field of view that is feasible at low cost. If the field of view of the device shown in US Patent Specification No. 5,050,966 were to be extended above approximately 40 degrees, the optical design would become overly complex due to the necessary first order properties required to illuminate the eye, and the third and higher order properties needed to compensate aberrations.

In virtual reality arcade games applications it has been usual to provide a head mounted display apparatus (HMD) in which a wide field of view is provided by two optical systems each comprising a plurality of lenses and a miniature liquid crystal display screen (LCD) to provide a binocular image to the user. Now that virtual reality games applications are being developed for the home market it is desirable that the unit cost of the HMD is kept to a minimum. LCD's are expensive components and it is desirable that a low-cost HMD comprises only a single LCD feeding a binocular image to the eyes of the user. One such solution is suggested in European Patent Specification No. EP 0 539 907 A2. This specification discloses an HMD shown in Figures 2 and 3 which comprises an LCD and magnifying lens mounted forwardly of the nose of a user, a beamsplitter feeding a separate complete image of the LCD respectively to two mirrors each mounted respectively in the line of sight of the user, and further magnifying lenses each mounted intermediate one of the mirrors and its respective eye of the user. It is understood that the arrangement described provides a construction wherein the bulk of optical apparatus disposed forwardly of the eyes is cumbersome.

The arrangement described in European Patent Specification No. 0 539 907 is understood to be fundamentally limited in the field of view that can be projected with adequate performance, by the non-rotationally symmetrical nature of the beamsplitting prism. As a consequence the two eyes of a user perceive images that are projected with different perspectives and the user looking toward the extremities of the field of view will see vertical disparities between the relative size of each of the binocular images. Such disparities are a fundamental property of prismatic beamsplitters and viewing them is well known to cause eye strain. This type of arrangement is therefore limited to projecting a field of view about 15 degrees wide and which results in a restricted, blinkered experience for the user.

It is an object of the invention to provide an optical system suitable for use in a head mounted display apparatus usable in conjunction with virtual reality software applications and which overcomes at least in part some if not all of the aforesaid disadvantages of prior art devices. It is a further object of the invention to provide an optical system that is suitable for

use in a head mounted display apparatus which projects a wide field of view from a single image source.

According to a first aspect of the invention a head mounted display apparatus having a display screen on which a video image can be displayed and having left and right exit pupils at which binocular images of said video image can be viewed, is characterised in that; it comprises a vertically offset beamsplitter having first and second mirrored surfaces the median planes of which are mutually inclined with said surfaces being disposed respectively above and below an axis extending therebetween, and further comprises at least one concave mirror, with the arrangement providing that said first mirrored surface and said concave mirror cooperate to deviate an optical path from said screen to permit viewing of an image at a first of said exit pupils and said second mirrored surface causes deviation of another optical path from said screen to permit viewing of another image at the other said exit pupil. Said video display screen desirably is a miniature LCD screen mounted forwardly of said exit pupils.

Preferably, said apparatus comprises left and right hand fold mirrors, said beamsplitter mirrored surfaces are semi-reflecting mirrors, said axis is generally coextensive with the optical axis of said concave mirror which is disposed forwardly of said screen and said exit pupils are disposed forwardly or rearwardly of the concave mirror, and in that said offset beamsplitter is mounted intermediate said display screen and said concave mirror and said fold mirrors are each disposed laterally either side of said offset beamsplitter with the arrangement providing that an initial image is displayed on the display screen, the initial image is projected forwardly through said offset beamsplitter to be incident on said concave mirror which reflects and focuses said image received, the reflected image is incident on reflective faces of the semi-reflecting mirror surfaces which divides the reflected image into two optical paths, a first of which is incident on the left hand fold mirror which reflects light toward said left exit pupil and the second of which is incident on said right hand fold mirror which reflects light toward said right exit pupil.

The apparatus may further comprise magnifying optics adapted to magnify an image received from the display screen and/or to collimate an aerial image formed by the concave mirror. Said magnifying optics may comprise a first lens or lens array disposed intermediate

said left hand fold mirror and said left exit pupil and a second lens or lens array disposed intermediate said right hand fold mirror and said right exit pupil. One or more of the lens of each of the lens arrays may be non-rotationally symmetrical about their respective optical axes and/or the lens arrays may be moveable along their respective optical axes to adjust focus of received images.

Typically, said semi-reflecting mirrors are substantially mutually perpendicular and may have substantially upright planar reflective surfaces. Generally, said display screen is a LCD video display mounted coaxially with the concave mirror and said right and left handed fold mirrors may be planar mirrors.

One or more further fold mirrors may be disposed intermediate said left hand fold mirror and said left exit pupil and one or more still further fold mirrors are disposed intermediate said right hand fold mirror and said right exit pupil. Angular adjustment may be provided for either or both said semi-reflecting mirrors and/or at least one of said fold mirrors to compensate optical misalignments that are caused by refraction through the semi-reflecting mirrors of said beamsplitter. Median planes of external surfaces of said semi-reflecting mirrors may be non-parallel.

The apparatus may further comprises baffles to block or absorb unwanted light and said left and right hand semi-reflecting mirrors may each be provided by a respective prism. It may further comprise a device permitting interocular adjustment of the lateral spacing of the left and right exit pupil.

Typically, the initial image is of a linearly polarised object, the beamsplitter is adapted to reflect one polarisation of light more than another and a polarisation retarding object is disposed intermediate the beamsplitter and the concave mirror with the arrangement providing that the polarisation retarding object facilitates enhancement of the light intensity transmitted and reflected by the beamsplitter. The concave mirror may be spherical or aspherical and may have one refracting surface and one reflecting surface and/or is provided by a lens/mirror array.

The apparatus may further comprise a moulded frame on to which the screen, beamsplitter, concave mirror, fold mirrors and magnifying optics are mounted so as to be accurately relatively positioned.

According to another aspect of the invention a head mounted display apparatus in accordance with said first aspect is characterised in that; monocular magnifying optics are disposed optically ahead of said screen and are adapted to magnify a complete image received therefrom, said offset beamsplitter is adapted to divide images received from said magnifying optics into first and second optical paths, and corresponding to each of said optical paths an associated plurality of reflective surfaces including one concave mirror surface with said plurality of reflective surfaces being collectively adapted to permit the viewing at the associated left or right exit pupil of a respective image received from the offset beamsplitter at infinity focus, with the arrangement providing that said first and second mirrored surfaces each correspond respectively to said first or said second optical path and with said first mirrored surface being offset to one side of the optical axis of the magnifying optics and said second mirrored surface being offset to the opposite side of said optical axis and further providing that the magnifying optics effect distortion of said video image to compensate aberrations induced by said concave mirror surface.

Preferably, said first and second mirrored surfaces of the beamsplitter are mutually substantially perpendicular planar surfaces with each said planar surface being generally upright. Typically, said display screen is disposed in a generally horizontal plane and has a generally upright optical axis, the optical axis of said magnifying optics is generally horizontal, and a planar mirror inclined relative to both the horizontal and vertical is disposed intermediate said display screen and said magnifying optics to deflect the path of the display screen optical axis so that after reflection from said planar mirror it extends generally coincident with the magnifying optics optical axis.

Desirably, each associated plurality of reflective surfaces includes in addition to the concave mirror a first plane mirror that reflects the image from the offset beamsplitter generally horizontally and rearwardly on to a second plane mirror that reflects the image downwardly on to a reflective surface of a planar semi-silvered beamsplitter that reflects the

image generally horizontally and forwardly on to said concave mirrored surface which then collimates said image by reflection through the planar semi-silvered beamsplitter so that it can be viewed at the associated left or right exit pupil.

The display screen may be a miniature LCD video screen. The magnifying optics may comprise at least one aspheric refracting surface and further may comprise an array of three coaxially mounted lenses. The material composition of each of the three lenses may be chosen so that in combination chromatic aberration of a magnified image is minimised. Typically, the magnified images can be viewed in binocular fashion substantially without parallax in a central field of view.

According to another aspect of the invention a head mounted display apparatus comprises a display screen on which a video image can be displayed, monocular magnifying optics disposed optically ahead of the screen and adapted to magnify a complete image received therefrom, a first beamsplitter adapted to divide images received from said magnifying optics into first and second optical paths, and corresponding to each of said optical paths an associated plurality of reflective surfaces including a concave mirror surface collectively adapted to permit the viewing at an associated exit pupil a respective image received from the first beamsplitter at infinity focus, with the arrangement providing that the first beamsplitter comprises first and second mirrored surfaces corresponding respectively to said first and second optical paths with median planes of the mirrored surfaces being mutually inclined and further providing that the magnifying optics effect distortion of said video image to compensate aberrations induced by said concave mirror surface.

In the following specific description all dimensions are given in millimetres and all angles in degrees unless otherwise stated or inferred. Preferred embodiments of the invention will now be described by way of example only and with reference to the accompanying drawings, in which:-

Figure 1 is a diagrammatic perspective view of optical components of a first embodiment, typically housed in a visor type head mounting;

Figure 2 is a ray trace diagram of the optical components shown in Figure 1 illustrating the light path viewed in vertical elevation from an LCD to the right hand exit pupil of a user;

Figure 3 is a ray trace diagram illustrating the light path viewed in horizontal plan from the LCD to the right hand exit pupil;

Figure 4 illustrates diagrammatically a planar mirrored beamsplitter arrangement which forms a part of the first embodiment;

Figure 5 illustrates by way of a plurality of associated diagrams the eventual shape of the exit pupils of the first embodiment;

Figures 6(a) to (c) illustrates schematically a second embodiment of the invention each viewing the second embodiment from a different direction as indicated;

Figure 7(a) and (b) shows two views from different directions of ray traces through the second embodiment;

Figure 8 is a diagrammatic perspective rear view of a third embodiment of the invention;

Figure 9 shows light ray paths through a horizontal section of an optical design of the third embodiment;

Figure 10 shows exit pupil shape and size projected through the third embodiment from various points on an object;

Figure 11 shows a horizontal section through the optical design of the third embodiment with selected ray paths illustrating how horizontal orientation and alignment of both projected images is the same;

Figure 12 is a diagrammatic perspective front view of a fourth embodiment of the invention;

Figure 13 shows light ray paths through a horizontal section of an optical design of the fourth embodiment;

Figure 14 shows a horizontal section through the optical design of the fourth embodiment with selected ray paths showing how horizontal orientation and alignment of both projected images is the same;

Figure 15 shows a horizontal section through a further embodiment, similar to the fourth embodiment, showing where polarisation selective components can be positioned to improve light transmission; and

Figure 16 shows a horizontal section of an example of the optical design of the third embodiment whose reference numbers are referred to in the following Table A to identify optical surfaces.

It should be appreciated that a head mounted display apparatus in accordance with any one of the described embodiments of the invention is adapted to be worn on the head of a user and that in use it is subject to spatial movement in all directions. Consequently, in the following description and in the claims the terms 'vertical' and 'horizontal' are taken to be mutually perpendicular orientations and are descriptive terms relating to the relative spatial disposition of components. They should be given their literal meanings only when the apparatus is correctly aligned with nominal horizontal and vertical planes. Also, in the following the description the term "surface pole" is defined as the intersection point of the incident optical axis on any given component surface.

Referring now specifically to Figures 1 to 7, embodiments of the invention will now be described having a vertically offset beamsplitter and two concave mirrors. An optical system of the first embodiment shown diagrammatically in Figure 1 comprises a plurality of elements with those relating to viewing by the right eye of a user being represented in Figure 3. The

optical system has three principal axes two of which X-X and A-A are shown on Figure 3. Axis X-X being a centre line of the optical system is the optical axis of a lens array of the magnifying system and axis A-A corresponds to the optical axis of the right eye of the user after it has been refracted through a planar beamsplitter 13 disposed in front of said eye. The refraction of beamsplitter 13 induces a vertical offset in the ray path so that axis A-A is typically slightly higher than the mid-point of the user's right eye. The third axis B-B (not shown) corresponds to the optical axis of the left eye of the user after it has been refracted through a planar beamsplitter 113 disposed ahead of that eye. In this embodiment the three axes are parallel and horizontal with axes A-A and B-B lying in the same horizontal plane disposed below axis X-X.

The magnifying system comprises a video image display screen provided by a miniature colour video LCD 1, a planar fold mirror (not shown) and the magnifying lens array comprising three co-axially mounted lenses 2,3,4. The planar front face of the LCD 1 typically faces downwards having its optical axis upright, i.e. directed vertically. The planar fold mirror is disposed between the screen 1 and lenses 2,3,4 and angled at 45 degrees to project the optical axis of the LCD 1 generally horizontally and forwardly toward lenses 2,3,4, i.e. along axis X-X.

The LCD screen 1 nominally generates a 14.224mm by 10.668mm high image and has a 1.0mm thick faceplate that is modelled as Schott K5 glass, i.e. of refractive index approximately 1.52 and Abbe dispersion value of approximately 55. The pole of the said planar fold mirror (not shown) is spaced along the optical axis of the LCD 1 from the faceplate by 13.6677mm. The said fold mirror has a clear aperture concentrically disposed about said pole and typically 36.0mm along the hypotenuse and 26.0mm wide. Also, said fold mirror is conveniently fabricated from polished glass that is coated with a reflecting material. The distance along the X-X axis between the said fold mirror and the pole of the first lens surface is 13.0mm. The surface construction of lenses 2,3,4 is listed as follows, starting from the surface nearest LCD 1 and taken in sequence:-

<u>Surface Form</u>	<u>Spherical Radius of Curvature (mm)</u>	<u>Clear Aperture Diameter (mm)</u>	<u>Separation to next surface (mm)</u>	<u>Material</u>
convex sphere	21.6498	24	8.26107	acrylic
convex asphere*	21.1132	24	3.49028	air
concave sphere	34.5209	24	2.98126	polycarbonate
concave sphere	25.401	23	2.00745	air
convex sphere	58.6466	26	10	acrylic
convex sphere	19.6757	26	7.18953	air

*Aspheric coefficients: $a_4=+6.064872e-05$; such that the surface sag = the sag of the base curve at a_4xy^4 ; the positive coefficient adds material to the lens edge.

A first vertically offset beamsplitter generally denoted 5 and shown in Figure 4 is mounted forwardly of the lenses 2,3,4 and comprises two planar mirrors 6,7 each having a generally upright rearwardly facing silvered surface respectively 8,9. The mirrors 6,7 are disposed at nominally 90 degrees relative to one another with mirror 6 being disposed above axis X-X and mirror 7 being disposed below axis X-X. In Figure 3 the mirror 7 is shown in chain outline. Surfaces 8,9 are each disposed in a generally vertical plane offset by 45 degrees from the horizontal axis X-X.

The silvered surfaces 8 and 9 nominally intersect at point P on the X-X axis. Axis E-E' shown in Figure 4 is nominally normal to axis X-X at point P and extends along the generally horizontal plane common to axes X-X and A-A. The arrangement is such that at point P mirrored surface 8 is disposed at an angle of nominally 45 degrees relative to axis E-E' and mirrored surface 9 is disposed at an angle of nominally 45 degrees relative to axis X-X. In practice to accommodate manufacturing tolerances a small clearance between surfaces 8 and 9 may be provided at point P. Also, in other embodiments of the invention the vertical disposition of mirrors 6,7 may be reversed. Typically, the two mirrors 6,7 of the first beamsplitter 5 could be moulded as one piece to ensure accurate relative disposition of mirrored surfaces 8,9 thereof.

Operatively the beamsplitter 5 results in light received from above the axis X-X by means of surface 8 being reflected through generally 90 degrees toward the left eye of the user as shown by the light ray path CC'. Similarly, light received from below the axis X-X by

means of surface 9 is oppositely reflected through 90 degrees toward the right eye of the user as shown by the light path DD'.

Associated with the right eye of the user an exit pupil 10 receives an image reflected from surface 8 of beamsplitter 5 by first light reflecting means comprising sequentially a first horizontal fold mirror 11, a first vertical fold mirror 12, a second planar beamsplitter 13 and a first concave mirror 14. Similarly, associated with the left eye of the user an exit pupil 110 receives an image reflected from surface 9 of beamsplitter 5 by second light reflecting means which is a mirror image of first light reflecting means and comprises sequentially a second horizontal fold mirror 111, a second vertical fold mirror 112, a second planar beamsplitter 113 and a second concave mirror 114. The disposition and operation of the first light reflecting means will hereinafter be described and it will be appreciated that as shown in Figure 1 the second light reflecting means is an oppositely handed version of the first light reflecting means.

The first horizontal fold mirror 11 is a planar mirror having a rearwardly facing silvered surface 15 disposed vertically and inclined at 45 degrees to the axes X-X and A-A. The intersection of the optical axis with surface 15 lies on the same height from axis A-A as the optical axis that traverses the centre of the magnifying lenses 2,3,4 provided that the said optical axis is parallel to axis A-A. The first vertical fold mirror 12 as shown in Figure 2 is a planar mirror having a forwardly facing silvered surface 16 extending in the 'z' direction as can be seen from Figure 3 and inclined relative to the 'x' and 'y' directions as defined by the Cartesian legend shown on Figure 2. This mirror may extend above the lens array 2,3,4. The surface pole of the surface 16 lies in the same plane as that of surface 15 and these points both lie in the vertical plane passing through horizontal axis A-A.

Second beamsplitter 13 is provided with a forwardly facing half-silvered surface 17 extending in the 'z' direction and inclined vertically which reflects light received from the first vertical fold mirror 12 on to the mirrored surface 18 of the first concave mirror 14. Surface poles of both second beamsplitter 13 and first concave mirror 14 lie on the optical axis A-A. The spatial arrangement of elements 11,12,13,14 of the first light reflecting means relative to the surface 8 of the first beamsplitter 5 provides that a magnified image of the LCD 1 can be viewed at infinity focus at the first exit pupil 10.

The optical axis X-X projected forwardly by the magnifying lenses 2,3,4 intersects the two beamsplitting plane mirrors 6,7 on their contacting edges, nominally point P shown in Figure 4, at a distance of 7.18953 from the pole of the nearest surface of lens 4. These mirrors 6,7 are disposed vertically from the axis X-X, i.e. one above and one below said axis, to split the image projected by the lenses 2,3,4 into two separate optical paths thereby providing two further projected images.

As aforescribed one said further image corresponding to that resulting from reflection off mirrored surface 8 is projected sideways and horizontally toward the right eye of a user to the second fold mirror 11, that reflects it horizontally and backwards to the third fold mirror 12. This third fold mirror reflects the image downwardly, but not precisely vertically, to the plane beamsplitter 13. The plane beamsplitter 13 reflects the image horizontally and forwardly to the concave mirror 14 that reflects the image horizontally and backwardly to be refracted by transmission through the aforesaid plane beamsplitter 13 to the exit pupil 10 and hence into the right eye of the user. It will be understood that the passage of the other further image, i.e. that resulting from reflection off surface 9, can be similarly described with reference to corresponding elements associated with exit pupil 110.

To define better the operation of the first embodiment reference is made to the diagrams of Figure 5. Each exit pupil 10,110 has a nominal circular exit pupil shown as 20 which can be traced back along the eye path as far as the first mirrored beamsplitter 5 where it will be appreciated only about half of the exit pupil 20 is subject to reflection by virtue of the vertical offset of mirrors 8,9. When viewed on axis, the left exit pupil 110 will result in reflected exit pupil shape 21 and similarly right exit pupil 10 results in reflected exit pupil shape 22. Typically, by virtue of some mismatch between properties of the beamsplitting mirrors and lenses there will be some vignetting of the exit pupils for beams not projected parallel to the optical axis. Consequently, viewing off axis will result in the shaded exit pupil shapes 23,24 for the left and right exit pupils 110,10 respectively.

The aforescribed analysis will yield by virtue of the disposition of the beamsplitting and reflective components of the optical systems of the invention images 25,26 being viewed

at exit pupils 110,10 respectively. It will be noted that images 25,26 lie on a horizontal axis X'-X' extending between exit pupils 110,10. Use of mirrors and beamsplitters causes rotation of the image as can be seen from representations of viewed exit pupil shapes 25,26. In some variants of the aforescribed design such rotation may lead to reversal of one of its axes, but such effects are the same for each of the two aforescribed optical paths. Therefore, the rotation of the LCD image and if necessary its reversal about the appropriate axis is sufficient to project images that are correctly aligned to the user.

For simplicity in describing constructional parameters of one half of the optical system, we define a Cartesian set of co-ordinates originating at the associated exit pupil and having a horizontal x-axis parallel to axis A-A, a vertical y-axis and a horizontal z-axis pointing inwardly toward the other exit pupil. Note that these Cartesian axes are not those shown for illustrative purposes in the accompanying drawings. The following table gives the Cartesian co-ordinates in millimetres of the poles of the optical surfaces of each component respectively:-

<u>COMPONENT DESCRIPTION</u>	<u>'x' co-ordinate</u>	<u>'y' co-ordinate</u>	<u>'z' co-ordinate</u>	<u>Angle to the Surface Norm to the Optical Axis at the Po</u>	
				<u>Angle to x-axis</u>	<u>Angle to y-a</u>
Beamsplitter Mirror	107.11	47.1633	32	45	90
Second Fold Mirror	107.11	54.163	0	45	90
Third Fold Mirror	57.113	54.163	0	52	38
Plane Beamsplitter (reflecting surface)	43.807	0.797	0	38	52
Concave Mirror	83.807	0.797	0	0	90
Plane Beamsplitter (refracting surface)	43.807	0.797	0	38	52
Plane Beamsplitter (refracting surface)	40	0	0	38	52

Co-ordinate values for the other half of the optical system can be calculated by reversing the z-axis for the above table so that the angles that surfaces make with the z-axis remain the same thereby generating a mirror image of the optical path of the aforescribed first half of the optical system. In addition to effect the correct mathematical transformation

for tabulated values the beamsplitter mirror must be translated vertically, so that its 'y' co-ordinate is increased by 14mm.

In use the optical system provides the user with a binocular magnified images of the LCD screen at infinity focus. The construction of the system is such as to minimise any parallax between the two binocular images particularly in a central portion of the field of view. Any external distortion that may be experienced can be reduced by masking the periphery of the images as and when desired.

The following table gives the form of the mirrors that occur in the optical path after the magnifying lenses 2,3,4:-

<u>COMPONENT</u>	<u>Surface Form</u>	<u>Clear Aperture</u>			<u>Material</u>
		<u>Shape</u>	<u>Width</u>	<u>Height</u>	
Beamsplitter Mirror	plane	rectangular	37	12	coated plastic
Second Fold Mirror	plane	rectangular	44	30	polished & coated glass
Third Fold Mirror	plane	rectangular	39	61	polished & coated glass
			(22 outwards & 17 inwards)		
Plane Beamsplitter (reflecting surface)	plane	rectangular	55	63	polished & coated glass
			(31 outwards & 24 inwards)	(26 up & 37 down)	
Concave Mirror	concave sphere ($r=116.415$)	rectangular	70	65	coated plastic
			(40 outwards & 30 inwards)		
Plane Beamsplitter (refracting surface)	plane	rectangular	45	55	polished & coated glass
			(25 outwards & 20 inwards)	(20 up & 35 down)	
Plane Beamsplitter (refracting surface)	plane	rectangular	45	55	polished & coated glass
			(25 outwards & 20 inwards)	(20 up & 35 down)	

The horizontal width and vertical height of the clear apertures are measured in the plane of each optical surface and so may not be actually horizontal or vertical though may be described figuratively as such. The clear apertures in the above table are oversized for simplicity of description. Actual ray paths will use a smaller area than that defined, but

rectangular apertures are specified that are generally centred on the associated optical axis. In particular, the beamsplitter mirror 6 will not reflect the beam over the whole height of the second fold mirror. However, the aperture specified is symmetrical about the optical axis and will therefore pass all the necessary rays in both halves of the optical system.

The thickness of each mirror 6,7 respectively of the plane beamsplitter 5 is typically 3mm measured in a direction normal to the corresponding optical surface 8,9. The fully reflecting coatings used throughout the aforescribed embodiments are generally fabricated by either sputtering or evaporating chrome or aluminium in a vacuum on to a substrate. Aluminium coatings will generally be protected from corrosion by a transparent layer over the top exposed surface. The semi-reflecting surfaces will likewise be coated, but with a more controlled thickness of metal which will tend to recommend the use of an evaporation deposition method in preference to sputtering for reasons of improved accuracy. Alternatively, the semi-reflecting surfaces may be coated by means of a dielectric coating process.

The LCD 1, lenses 2,3,4 and mirrors 8,9,11,12,13,14 of the first embodiment are mounted within a head mounted visor (not shown) to provide a lightweight construction. This visor further comprises signal input means to drive the LCD and may contain position sensing means to provide feedback relating to the spatial position and orientation of the user's head.

In another embodiment of the invention (not shown) the LCD 1 may be mounted horizontally parallel to axis X-X in association with a mirror adapted to reflect the LCD image toward the lens array 2,3,4. The LCD may be back or side lit in either embodiment. It has been appreciated by the inventor that the cost savings of using a single LCD screen permit for only moderate increase in cost the use of an LCD having higher resolution than is normal for twin LCD designs. Advantageously, this enables the aforescribed apparatus to provide an improved resolution.

It has been suggested that in a yet further embodiment of the invention the concave mirrors 14,114 may themselves be half-silvered beamsplitters enabling the user to receive light incident from the surrounding environment so that the LCD generated images are

superimposed on the user's line of sight. In this case, the outer surface of each concave mirror 14,114 which would otherwise be opaque must be optically smooth and shaped to compensate aberrations of the image of the surrounding environment which are induced by the concave reflecting surface upon refraction of light transmitted therethrough. This leads to the outer surface of each concave mirror 14,114 being generally parallel to the corresponding inner reflecting surface 18,118. Other designs may have the outer surfaces semi-reflecting and the inner surfaces 18,118 transparent so that for each concave mirror, now concave beamsplitter 14 or 114, the corresponding displayed image refracts through the inner surface, reflects off the outer surface and then refracts once more through the inner surface whilst the external image refracts in turn through the outer and inner surfaces.

The aforescribed first embodiment is a low cost device which will normally not have any interocular adjustment, i.e. user adjustment of the distance between the exit pupils 10,110. As a consequence the exit pupils 10,110 must be generally wide enough to accommodate viewing without substantial vignetting by users with a wide range of interpupillary distances. For best performance the arrangement of the two plane mirrors 6,7 forming the beamsplitter 5 is such as to project the maximum exit pupil width which dictates that they should be displaced vertically from each other as aforescribed.

Images are produced from a single LCD 1 and projected by the aforescribed paired binocular optical systems into each eye of the user. These paired systems should have no substantial parallax between them and therefore differences in optical paths must be minimised. Because of the vertical offset in the first pair of plane mirrors 6,7 that form beamsplitter 5 it is necessary to focus the magnifying lens to match the height of rays projected into the eye at equal vertical field angles. This may be determined by tracing parallel rays respectively from each exit pupil 10,110 to the LCD 1, but simulating the vertical offset of each corresponding pupil by having different vertical ray co-ordinates. An out of focus optical system will cause rays to intersect the LCD 1 at different heights. These are brought to the same co-ordinates by adjusting the position of the magnifying lenses 2,3,4.

In use both eyes will see some distortion of the image shape due to aberrations in the magnifying lenses 2,3,4 and concave mirrors 14,114, but these do not create the more critical

parallax errors if they are the same for both eyes. Naturally, this will tend to be the case as the aforescribed design has nominally identical aberrations although parallax may be introduced by manufacturing errors. The magnifying lenses 2,3,4 are adapted to provide that an associated aerial image is projected near each plane beamsplitter 13,130 that is a distorted image of the LCD 1 and that compensates for some of the aberrations induced on reflection from the respective concave mirror 14,114. The concave mirrors 14,114 then collimate the aerial images to project an image of the aperture of the magnifying lenses 2,3,4 to form exit pupils such as aforescribed with reference to Figure 5.

Typically, the aforescribed embodiment offers a wide field of view in excess of 50 degrees together with a reasonably long eye relief, i.e. the respective distance between each second plane beamsplitter 13,113 and the corresponding exit pupil 10,110. This has been achieved with minimal component complexity. By manufacturing in high volume from suitable moulded plastics parts the cost of the optics systems described can be brought down to levels consistent with a consumer product suitable for home use, for example.

In the first embodiment, the second plane beamsplitters 13,113 are fabricated from a single substrate. This substrate is coated over separate clear apertures required to project each image corresponding respectively to exit pupils 10,110. As a result of the long eye relief desired by most users, the concave mirrors 14,114 must be large to reflect over a wide field of view and will suitably meet in the middle of a helmet configuration housing the optical system. It is preferable to mould left and right concave mirrors 14,114 integrally. With a wide field of view, the width of each concave mirror 14,114 would interfere with the opposite image, i.e. that reflected by the other mirror 114,14 respectively. Consequently, it may be necessary to vignette the horizontal field of view projected into each exit pupil 10,110. This is acceptable because the user's brain will compensate the loss of part of one image with the other image, i.e. a blind spot will not be perceived.

A second embodiment of the invention shown in Figures 6 to 7 is an optical design which similarly to the aforescribed embodiments projects collimated binocular images over a wide field of view from a single LCD 300. The design is further illustrated with reference to Figures 7 by tracing light backwards from the eye of a user to the LCD 300 as exit pupil 301,

corresponding to a nominal eye position, defines the generation of ray co-ordinates. Thus, in the following description the terms describing refraction, reflection and the inducement of aberrations effectively apply to the projection of images from the eye to the LCD 300, i.e. in reverse order. From Fermat's principle the optical properties so calculated are identical to the analysis of light travelling in the opposite direction, i.e. from the LCD 300 to the exit pupil 301. Only the operation of one half of the design will be described in detail as it will be appreciated that similar elements and interaction thereof will result in the desired image for the other half of the design.

One eye views through exit pupil 301 shown in Figures 6 to 7 an image of an internal lens aperture 302 (shown in Figure 7a.) which is well defined and nominally circular. The exit pupil 301 is further vignetted by an offset mirror assembly 303 which is structurally and operatively similar to the mirrored beamsplitter 5 of the first embodiment (as shown in Figure 4). This assembly 303 directs one half of the exit pupil into one eye and the other half into the other eye.

Rays are traced from the exit pupil 301 over a wide field of view to intersect a plane beamsplitter 304 and refracting through that they refract through and reflect off a remote outer surface of a concave mirror 305. For convenience of manufacture the planar beamsplitter 304 is common to both halves of the design, i.e. it is common to both eyes, and the required two concave mirrors 305 are integrally formed adjacent one another. Rays are reflected back to the plane beamsplitter 304 where they are now reflected upwards toward a corresponding plane mirror 306. The concave mirror 305 has converging optical power that serves to converge the rays so that they pass through the extent of the limiting lens aperture 302. As a consequence of this, concave mirror 305 forms an aberrated aerial image close to the beamsplitter 304.

Plane mirror 306 reflects rays sideways into a middle region of the optical design and on to the offset mirror beamsplitter assembly 303. This again reflects the rays vertically so that the combined operation of plane mirror 306 and of the associated mirror of beamsplitter assembly 303 induces no effective image rotation or parity error. The other half of this optical design operates as a mirror image of the aforescribed first half of the design utilising the

other mirror of the offset beamsplitter assembly 303. The two plane mirrors of beamsplitter assembly 303 are arranged so that the top half of the limiting lens aperture 302 is reflected into one eye and the bottom half is reflected into the other eye. This orientation is necessary to maximise the width of the projected exit pupils 301 at the expense of the height thereof to cover the widest variation in user's inter-pupillary distance (IPD).

In this second embodiment a monocular optical magnifying system is provided by lenses 307,308,309 arranged sequentially and coaxially. The aperture of lens 309 immediately adjacent and disposed above beamsplitter assembly 303 provides the lens aperture 302. To provide a compact design it is necessary to project a fairly wide field of view in the space between the lens 309 and the offset mirror beamsplitter assembly 303. Thus, any mismatch in the longitudinal position of the offset mirror beamsplitter assembly 303 and lens 309 may cause some vignetting in the shape of exit pupil 301 as it is projected across the field of view.

Vignetting of the field of view occurs at inner edges of the concave mirror 305, i.e. immediately adjacent the other mirror 305, which cannot extend inwards beyond half the average user's IPD without impinging on the required aperture of the adjacent concave mirror. The plane beamsplitter 304 must be sufficiently forward of the exit pupil 301 to clear spectacles and the user's forehead thereby requiring the concave mirror 305 to be even further forward therefrom. As a consequence extreme inner rays intersect the concave mirror 305 at over half the average IPD and must be vignetted. This presents a limitation on the use of the design as the user may view a vignetted image which requires the brain to compensate for binocular disparity. Also, longitudinal mismatch between the offset beamsplitter assembly 303 and lens 309 causes vignetting of the vertical field of view.

Rays reflected from the offset mirror of beamsplitter assembly 303 intersect lenses 307,308,309. These lenses may be aspheric or have only spherical surfaces, although in this further embodiment only lens 307 is aspheric. The relay lens assembly of lenses 307,308,309 projects the aerial image formed by concave mirror 305 on to the LCD 300 in such manner as to compensate aberrations induced by the concave mirror 305. Primary aberration compensation occurs as a consequence of the concave mirror 305 induces Petzval Field Curvature that is of opposite sign to the same form of aberration produced by the relay lens

assembly. Spherical aberration, coma, astigmatism and distortion are also compensated though it is believed that minimal spherical aberration and distortion are induced by the concave mirror 305.

The concave mirror 305 is free of chromatic aberration so the lenses 307,308,309 must collectively be substantially free of the same. The relay lenses projects rays from most of the lens aperture 302 on to the exit pupil 301 for any field position thereby resulting in the dominant type of chromatic aberration being the variation of focus with colour which has the wrong form of compensation requirement than can be provided by the eye or CGI software. To compensate for this chromatic aberration (which if uncompensated for could result in a loss in resolution) different materials are chosen for each of the lenses 307,308,309.

A 'see-through' capability is viable with the aforescribed design by making the concave mirror 305 a beamsplitting visor that has an outer refracting surface that is closely spaced from and approximately parallel with the reflecting surface or by making an outer reflective surface a refracting surface also. In such circumstances the concave mirror 305 may be fabricated with a semi-reflecting beamsplitter coating that partially reflects the LCD image and partially transmits the outside scene.

A typical optical design in accordance with the said second embodiment is tabulated below starting with one exit pupil 301 and taking each surface in turn ending with the common LCD 300. Dummy surfaces that do not refract or reflect have been inserted to aid analysis and are indicated by a bracketed 'D'. Note that all measurements are in millimetres.

The following details relate to table 1 below:-

*A - Convex Aspheric Radius = 17.0734; $a_4 = -1.886765e-07$; $a_6 = -4.7606627e-08$ and where negative coefficients increase the lens edge.

*B - Concave Aspheric Radius = 242.213; $a_4 = 5.2127814e-05$ positive coefficients increase the lens edge.

*C - Convex Aspheric Radius -20.1594; $a_4 = 6.0394345e-05$; $a_6 = 4.742696e-08$ and positive coefficients increase the lens edge.

Table 1. Surface Data:

<u>SURFACE NO.</u>	<u>Radius of Curvature</u>	<u>Clear Aperture</u>	<u>Distance to Next Surface</u>	<u>Materials of Following Space</u>
1 (Exit Pupil)	infinite	16.0 diameter	40	air
2 (D)	infinite		0	air
3	infinite	57 x 110	4.24264	Schott BK7
4	infinite	59 x 110	0	air
5 (D)	infinite		50	air
6	-115.005/concave sphere	100 x 80	-50	mirror in air
7	infinite		0	mirror in air
8 (D)	infinite	66 x 110	40	air
9 (D)	infinite		8.36236	air
10 (D)	infinite		-8.36236	mirror in air
11 (D)	infinite	52 x 34 (offset horiz. by 5)	-32	air
12 (D)	infinite		0	air
13 (D)	infinite		0	air
14 (D)	infinite		0	air
15 (D)	infinite		0	air
16	infinite		0	mirror in air
17 (D)	infinite	32 x 19	0	air
18 (D)	infinite		10	air
19 (D)	infinite		7	air
20	convex aspheric (see *A below)	26 diameter	10	acrylic
21	-51.2707/convex sphere	26 diameter	2.02565	air
22	-32.0474/concave sphere	23 diameter	2.98	polycarbonate
23	concave aspheric (see *B below)	24 diameter	5.28645	air
24	+20.26225/convex sphere	24 diameter	8.26	acrylic
25	convex aspheric (see *C below)	24 diameter	13	air
26 (D)	infinite		0.94559	air
27 (D)	infinite		-0.657	air
28	infinite	20 x 20	1	Schott K5
29	infinite	14.224 x 10.668		air

Table 2. Global Co-ordinates:

<u>Surface No.</u>	<u>'x' co-ordinate</u>	<u>'y' co-ordinate</u>	<u>'z' co-ordinate</u>	<u>Angle to the Surface Normal to the Optical Axis at the Pole</u>	
				<u>angle to x axis</u>	<u>angle to y axis</u>
				<u>angle to x-axis</u>	<u>angle to y-axis</u>
1	0	0	0	0	90
2	40	1.007	0	0	90
3	40	1.007	0	45	45
4	44.243	1.007	0	45	45
5	44.243	1.007	0	0	90
6	94.243	1.007	0	0	90
7	44.243	1.007	0	45	45
8	44.243	1.007	0	90	0
9	44.243	41.0007	0	90	0
10	44.243	49.363	0	90	37.677
11	44.243	41.0007	0	90	90
12	44.243	41.0007	32	90	135
13	24.243	41.0007	32	90	135
14	44.243	41.0007	32	90	90
15	44.243	41.0007	32	90	37.659
16	34.243	41.0007	32	90	37.659
17	44.243	41.0007	32	90	90
18	44.243	41.0007	32	90	0
19	24.243	51.0007	32	90	0
20	44.243	58.0007	32	90	0
21	44.243	68.0007	32	90	0
22	44.243	70.0263	32	90	0
23	44.243	73.0063	32	90	0
24	44.243	78.2928	32	90	0
25	44.243	86.5528	32	90	0
26	44.243	99.5528	32	90	0
27	44.243	100.498	32	90	0
28	44.243	99.8414	32	90	0
29	44.243	100.841	32	90	0

Table 2 above details global co-ordinates of the pole of each surface given in the table 1 above. These co-ordinates are given relative to a Cartesian co-ordinate system having its origin situate at the exit pupil 301. The x-axis extends forwardly of the origin, the y-axis

extends upwardly and the z-axis inwardly toward the other exit pupil. Note that all dimensions are in millimetres and all angles are in degrees.

In the aforedescribed embodiments of the invention the planar beamsplitters 5,302 are each described as being a vertically offset mirror beamsplitter assembly having vertically disposed and nominally mutually perpendicular planar mirrors. It should be understood that the ambit of the invention as claims should embrace design variants in which such a beamsplitter may have non-planar reflective surfaces; and that the two reflective surfaces may be adjustable rotationally and angularly relative to one another. In particular, rotational adjustment will permit interocular adjustment, for example.

Referring now to Figures 8 to 16, embodiments of the invention will be described which are in the form of a binocular magnifier comprising a vertically offset beamsplitter similar to that shown in Figure 4 but having half-silvered mirrored surfaces and further having a single concave mirror. Such a magnifier may be incorporated into a visor type head mounted display suitable for virtual reality applications wherein the image from a LCD video display screen provides an object that can be viewed in binocular fashion through ports or eyepieces of the visor worn by an observer. Alternatively, the binocular magnifier could have other uses and/or applications and any limitations of the claims to use in a head mounted display should not be taken to estop or preclude the Applicant from broadening the claims in this or any divisional Application derived herefrom to encompass other such uses. Such a magnifier could be used in a wide range of industries where images must be projected at a near infinity conjugate.

In the third embodiment shown in Figures 8,9 and 11 a viewed object is closer to the observer than a concave mirror, whilst in the fourth embodiment shown in Figures 12,13 and 14 the object is farther from the observer than the concave mirror. The following description relates to both the third and fourth embodiments and consequently like numerals denote like parts in the corresponding drawings.

For the purpose of easing calculation of ray paths through embodiments of the invention and for defining relative positions of optical components, the optical axis is defined

as a ray that leaves the exit pupil in a direction that is normal to said exit pupil and is traced in the reverse direction to the point of projection backwards through the described optical design by normal refraction and reflection. Two such optical axes exist, i.e. relating respectively to left and right exit pupils. These ray paths are a mathematical model rather than actually occurring in practice as the apertures of the beamsplitters vignette and obstruct them. As will be described use of a vertically offset beamsplitter arrangement results in the shape of projected exit pupils being non-symmetrical about the respective optical axes.

With reference to Figures 8 and 9, and 12 and 13, light from an object 501 that is projected into one of two eyes of an observer traverses a semi-reflecting beamsplitter 502 and impinges on a spherical or aspherical concave mirror 503 that reflects and focuses an image of the object. A magnified aerial image of object 501 is formed near to point 504 on an optical axis 509 being typically the optical axis of the observer's said one eye. The light reflected from the concave mirror 503 intersects again on the semi-reflecting beamsplitter 502, where part of it is reflected at near 90 degrees to its original path. The reflected image is projected by a plane mirror 510 into an associated eyepiece sub-assembly 505, which is formed by two identical lenses 506 (shown part cut away). The eyepiece sub-assembly 505 collimates and projects the aerial image 504 into the eye thereby forming an exit pupil 507 as a real image of the combined shape of the concave mirror and beamsplitter. A second semi-reflecting beamsplitter 508 is disposed immediately below the first beamsplitter 502 with their respective half-silvered mirrored surfaces being mutually substantially perpendicular each being disposed vertically. The beamsplitter 508 reflects the optical axis 509 in the opposite direction to that effected by beamsplitter 502. It will be understood that beamsplitters 502, 508 together form a vertically offset beamsplitter similar to that illustrated in Figure 4, but differing in function by virtue of its mirrored surfaces being half-silvered, i.e. permitting light transmission in one direction and light reflection in the other.

Should the observer perceive light traversing the binocular magnifier along unwanted paths, so that resultant images are misaligned or out of focus with other images, then thin and flat light baffles can be placed adjacent the beamsplitter 502 and 508 to block unwanted rays. Light that is reflected into the top of the wrong eyepiece by the beamsplitter 502 can be blocked by placing a thin baffle that is aligned normal to the object and vignettes the top half

of the optical path. Light that is correctly reflected by beamsplitter 508 will then pass underneath the said baffle. Similarly, a baffle can be placed near beamsplitter 508 to block unwanted reflections into the bottom optical path. Light that is transmitted through one beamsplitter and reflected by the other can be blocked by a baffle that is aligned horizontally and placed between the two beamsplitters 502 and 508.

Referring to Figures 9 and 13, the horizontal widths of the plane mirrors 510, the beamsplitters 502,508 and concave mirror 503 are chosen to project the limiting rays 511 shown without vignetting.

Figure 10 shows the resultant size of the projected exit pupil for the third embodiment. In Figure 10, a typical object 521 is shown with 5 points denoted 516,517,518,519 and 520. The size of the exit pupil is calculated by tracing rays from the exit pupil to each point in turn, and calculating which rays are vignetted by the optical components and which rays are transmitted or reflected. The shaded areas enclosed by the lines 525,526,527,528 and 529 in Figure 10 show the calculated extent of the exit pupils that are projected respectively from points 516,517,518,519 and 520 on the object, i.e. point 516 projects the exit pupil 525, point 517 the exit pupil 526, etc..

Circle 524 represents a nominal exit pupil that is 20 millimetres diameter for the design illustrated and which is centred on the optical axis 509. The optical axis 509 intersects the exit pupil at point 522 whereas point 523 is the estimated position for the centre of the observer's eyeball when placed for best viewing of the projected image. Points 522 and 523 are in the same positions in all the diagrams shown.

Orientation of one axis of viewed images is reversed because of the combined effect of the corresponding semi-reflecting beamsplitter 502 or 508 and plane mirror 510. In addition the whole image is inverted by the action of forming an intermediate image (at 504). This can be compensated for by adjusting the image displayed on the LCD object, i.e. it may be reversed so as to face 'back to front' thereby reversing the image in one axis only. Alternatively, one axis of the image may be reversed by placing an additional plane mirror in

the optical path adjacent the object, or by placing an additional plane mirror in each optical path between 'eyepieces' and the respective beamsplitter 502 or 508.

In Figure 11 it is illustrated that parallel images seen by the observer's eyes. In this third embodiment the beamsplitters 502 and 508 are not precisely mutually perpendicular thereby correcting a horizontal offset induced by refraction through the beamsplitters. The optical axes 509 are traced in parallel directions from the exit pupils 507 backwards to the object, and are reflected off the beamsplitters 502 and 508 in slightly different paths 509a and 509b. These paths 509a and 509b are reflected back through the beamsplitters 502 and 508 by the concave mirrors 503 on to the same point in the object 524. In this third embodiment, the optical axes 509 are parallel in both halves of the optical system, i.e. corresponding to the left and right eye of the observer, respectively from the exit pupil 507 to the plane mirror 510, and from the plane mirror 510 to the beamsplitter 502 or 508. The horizontal rays 512 enter each eye in parallel directions, and it can be seen that they leave the same point on the object. It is obvious that the vertical orientation of each image is identical. Likewise, the images projected from the fourth embodiment are also parallel, as can be seen from Figure 14 where horizontal rays 513 leave the same point on the object and enter the left and right eyes in parallel.

In the aforescribed third and fourth embodiments, the light transmission is normally limited to below 25 percent of the LCD object brightness as the light has to transmit through and reflect off the same beamsplitter in each path. In order to maximise the transmission, both reflection and transmission of each beamsplitter 502,508 must be as close to 50 percent as possible. Advantageously, LCD's emit linearly polarised light which can be permit an increase in the light transmission if suitable polarising components are used.

Polarising components can be added to improve transmission as shown in Figure 15. Here the object in the form of a LCD 501 incorporates a linear polariser 514. This typically polarises the light so that the electric field of the LCD is aligned horizontally. Light is transmitted through the now polarising beamsplitter 502 to a quarter wave plate 515 placed in front of the concave mirror 503. The quarter wave plate 515 rotates the plane of polarisation by 90 degrees before it is reflected back to the beamsplitter 502. This new polarisation is

selectively reflected by the beamsplitter 502. The beamsplitter coating can be fabricated cheaply from a single layer of an oxide of titanium.

It is not essential that the concave mirror 503 is a single component. In the aforescribed embodiments it is a simple spherical surface that reflects the light off a mirrored surface closest to the object. Aberration compensation may be improved by making that said surface aspheric or by adding more optical surfaces. For example, the mirror 503 could have a front refracting surface that transmits light through to a reflective rear surface. Additionally, one or more lenses could be placed intermediate a concave reflective surface and the LCD object.

The optical construction of one half of the binocular magnifier for the third embodiment is given in the following Table A, which refers to the construction shown in Figure 16. This table gives the co-ordinates of the positions of the poles, or centres, of each optical surface taken in turn relative to an origin using rectilinear (x,y,z) co-ordinates. The origin is defined as a point on the exit pupil, and the x-axis is defined as being normal to the said exit pupil. Table A consists of 9 columns, namely in order:-

- the surface number as shown in Figure 16;
- the optical surface radius of curvature (positive numbers being convex, negative being concave);
- the optical surface aperture size ('d' referring to diameter, alternatively if rectangular 'h' refers to the horizontal dimension whilst 'v' refers to the vertical);
- the 'x' co-ordinate of the pole of the optical surface relative to the origin;
- the 'y' co-ordinate of the pole of the optical surface relative to the origin;
- the 'z' co-ordinate of the pole of the optical surface relative to the origin;
- the angle that the optical surface makes to the x-axis of the origin in degrees;
- the material defining the space between two optical surfaces, and
- the refractive index of the aforesaid material at the 587.6 nanometer wavelength of the sodium d line.

The last two columns of Table A refer to the space following the surface number specified, i.e. material specified for surface 4 (S4) is that found intermediate surfaces 4 and 5

(S4-S5). Surfaces S3 and S4 are identical and aspheric. Table B gives the aspheric coefficients used in later mentioned equation that define the surface. Table C gives the object size and field of view projected from the design given in Table A.

The sag of the surface is defined by the distance to any point on the surface from a plane that is normal to the optical axis and includes the pole of the optical surface. Sag is measured in a direction normal to the said plane. The pole is defined as the point where the optical axis intersects the optical surface. If the distance of any point on the optical surface to the optical axis, in a direction normal to the said optical axis, is defined as 'R'; and the sag of the spherical surface defined by the radius specified in Table A is 's'; then the sag of the actual asphere is given by the equation:-

$$\text{sag} = s + [a_4 \times R^4] + [a_6 \times R^6]$$

where R^4 means R raised to the power of 4, R^6 means R raised to the power 6, a_4 and a_6 are aspheric coefficients and positive coefficients reduce the thickness of the lens.

Table A: Data Describing a Binocular Magnifier Design

Surface	Radius	Aperture	X	Y	Z	Angle	Material	Refractive Index
S1	infinity	20d	0	0	0	90	air	1
S2	73.399	42d	30	0	0	90	acrylic	1.490082
S3	33.651	42d	40	0	0	90	air	1
S4	33.651	42d	41	0	0	90	acrylic	1.490082
S5	73.399	42d	51	0	0	90	air	1
S6	infinity	32h x 32v	91	0	0	45	air	1
S7	infinity	56h x 30v	95.98	-36.92	15	44.6	air	1
S8	-70.722	52h x 70v	121	-32	0	90	air	1
S9	infinity	56h x 30v	95.98	-36.92	15	44.6	crown glass	1.522489
S10	infinity	56h x 30v	94.93	-37.98	15	44.6	air	1
S11	infinity	15h x 11v	59.9	-32	0	90	air	1

Table B: Aspheric Coefficients of Surfaces S3 & S4 defined in Table A

a4 coefficient (units: mm to power -3)	a6 coefficient (units: mm to power -6)
-4.901794e-06	-3.678384e-09

Table C: The Field of View of the Binocular Magnifier Design Given in Table 1

Horizontal field of view (degrees)	Vertical field of view (degrees)
45.2	33.5

When the semi-reflecting beamsplitters 502,508 transmit light, they act as components that are not rotationally symmetrical about the optical axis thereby introducing non-rotationally symmetrical aberrations. Such aberrations can be kept small by using relatively thin beamsplitters 502,508 fabricated from a material with low refractive index. Consequently, crown glass beamsplitters of less than 3 mm thickness are desirable. The aforescribed non-rotational symmetry also deviates the transmitted light paths laterally. Light projected from the centre of the object LCD through the beamsplitters 502,508 that are aligned horizontally will be deviated horizontally, but light entering the left hand 'eyepiece' will be deviated in the opposite direction to light entering the right hand 'eyepiece'. This results in the light paths projected into each eye from the centre of the object being misaligned unless compensated.

One compensation method is to rotate each eyepiece and plane mirror 510 about the intersection point of the optical axis with the plane mirror, such that the field of view projected into each eye is deviated by an equal and opposite angle to that projected into the opposite eye. This creates an angular difference between the two images that compensates for the angular error introduced by the beamsplitters. Alternatively as aforescribed with reference to Figure 11, the relative angular disposition of beamsplitters 502,508 may be non-perpendicular to compensate for potential angular misalignment of reflected images.

Embodiments of the current invention offer advantages over conventional optical designs by providing a high magnification of a small object, compact design and wide field of view, whilst using low cost components. Embodiments of the invention described relate to

binocular magnification of single objects that are small compared to the interpupillary separation of the eye, i.e. the objects are typically less than 25mm across. Desirably, the projected field of view is greater than 30 degrees. This requires that such an optical design has a focal length of less than 50mm, though more typically 20mm. Consequently, a conventional 'bi-ocular' magnifier incorporating a separate lens assembly for each eye is not feasible because the separation of the eyes is too large in comparison to the maximum viable focal length.

In the aforescribed embodiments the misalignments between two projected images and their respective aberrations are generally sufficiently small to allow an observer to use the devices for long periods of time without eyestrain. It is desirable that adjustment is not required to match the observer's interpupillary separation or for focus. Advantageously, designs in accordance with the invention can project images over sufficiently large exit pupils to remove any need for interpupillary adjustment and with sufficient eye relief (i.e. distance from the last optical surface to the user's eye) to permit the user to wear spectacles.

An advantage provided by the aforescribed vertically offset beamsplitters is that the number of times that images are subject to semi-reflection and/or semi-transmission is kept to a minimum thereby improving final image brightness. In the aforescribed designs optical components are usually kept symmetrical about a common LCD optical axis (although this is not essential). The respective vertically offset beamsplitters therefore project the top half of viable light paths into one 'eyepiece' and the bottom half into the other 'eyepiece', vignetting the beam accordingly. Each eyepiece projects the image of the object over an exit pupil that is itself a real image of the corresponding concave mirror and beamsplitter. Thus, each exit pupil, which determines the size of the projected beam at each eye, is halved in size by the lateral offset of the beamsplitters. The top half of the exit pupil is projected into one eye and the bottom half into the other. The axis connecting the centres of the two observer's eyes is 'kept' horizontal by rotating the whole optical design assembly to compensate for any vertical offset and by rotating the LCD object in the opposite sense to keep the displayed image aligned to the horizontal axis.

CLAIMS:

1. A head mounted display apparatus having a display screen (1) on which a video image can be displayed and having left and right exit pupils (7) at which binocular images of said video image can be viewed, characterised in that; it comprises a vertically offset beamsplitter having first and second mirrored surfaces (2,8), the median planes of which are mutually inclined with said surfaces being disposed respectively above and below an axis extending therebetween, and further comprises at least one concave mirror (3), with the arrangement providing that said first mirrored surface and said concave mirror cooperate to deviate an optical path from said screen to permit viewing of an image at a first of said exit pupils and said second mirrored surface causes deviation of another optical path from said screen to permit viewing of another image at the other said exit pupil.

2. Apparatus in accordance with claim 1, characterised in that; said video display screen is a miniature LCD screen mounted forwardly of said exit pupils.

3. Apparatus in accordance with claim 1, characterised in that; it comprises left and right hand fold mirrors (510), said beamsplitter mirrored surfaces are semi-reflecting mirrors (502,508), said axis (509) is generally coextensive with the optical axis of said concave mirror (503) which is disposed forwardly of said screen (501) and said exit pupils (507) are disposed forwardly or rearwardly of the concave mirror (503), and in that said offset beamsplitter (502,508) is mounted intermediate said display screen (501) and said concave mirror (503) and said fold mirrors (510) are each disposed laterally either side of said offset beamsplitter with the arrangement providing that an initial image is displayed on the display screen (501), the initial image is projected forwardly through said offset beamsplitter (502,508) to be incident on said concave mirror (503) which reflects and focuses said image received, the reflected image is incident on reflective faces of the semi-reflecting mirror surfaces (502,508) which divides the reflected image into two optical paths, a first of which is incident on the left hand fold mirror (510) which reflects light toward said left exit pupil (507) and the second of which is incident on said right hand fold mirror (510) which reflects light toward said right exit pupil (507).

4. Apparatus in accordance with claim 3, characterised in that; it further comprises magnifying optics (505) adapted to magnify an image received from the display screen and/or to collimate an aerial image formed by the concave mirror.
5. Apparatus in accordance with claim 4, characterised in that; said magnifying optics comprises a first lens or lens array (505) disposed intermediate said left hand fold mirror (510) and said left exit pupil (507) and a second lens or lens array (505) disposed intermediate said right hand fold mirror (510) and said right exit pupil (507).
6. Apparatus in accordance with claim 5, characterised in that; one or more of the lens (506) of each of the lens arrays are non-rotationally symmetrical about their respective optical axes.
7. Apparatus in accordance with claim 5 or claim 6, characterised in that; the lens arrays (505) are moveable along their respective optical axes to adjust focus of received images.
8. Apparatus in accordance with any one of claims 3 to 7, characterised in that; said semi-reflecting mirrors (502,508) are substantially mutually perpendicular.
9. Apparatus in accordance with any one of claims 3 to 8, characterised in that; semi-reflecting mirrors have substantially upright planar reflective surfaces.
10. Apparatus in accordance with any one of claims 3 to 9, characterised in that; said display screen is a LCD video display (510) mounted coaxially with the concave mirror (503).
11. Apparatus in accordance with any one of claims 3 to 10, characterised in that; said right and left handed fold mirrors (510) are planar mirrors.
12. Apparatus in accordance with any one of claims 3 to 11, characterised in that; one or more further fold mirrors are disposed intermediate said left hand fold mirror (510) and said left exit pupil (507) and one or more still further fold mirrors are disposed intermediate said right hand fold mirror (510) and said right exit pupil (507).

13. Apparatus in accordance with any one of claims 3 to 12, characterised in that; angular adjustment is provided for either or both said semi-reflecting mirrors (502,508) and/or at least one of said fold mirrors (510) to compensate optical misalignments that are caused by refraction through the semi-reflecting mirrors (502,508) of said beamsplitter.

14. Apparatus in accordance with any one of claims 3 to 13, characterised in that; median planes of external surfaces of said semi-reflecting mirrors (502,508) are non-parallel.

15. Apparatus in accordance with any one of claims 3 to 14, characterised in that; it further comprises baffles to block or absorb unwanted light.

16. Apparatus in accordance with any one of claims 3 to 15, characterised in that; said left and right hand semi-reflecting mirrors (502,508) are each provided by a respective prism.

17. Apparatus in accordance with any one of claims 3 to 16, characterised in that; it further comprises a device permitting interocular adjustment of the lateral spacing of the left and right exit pupil.

18. Apparatus in accordance with any one of claims 3 to 17, characterised in that; the initial image is of a linearly polarised object, the beamsplitter is adapted to reflect one polarisation of light more than another and a polarisation retarding object (515) is disposed intermediate the beamsplitter (502,508) and the concave mirror (503) with the arrangement providing that the polarisation retarding object (515) facilitates enhancement of the light intensity transmitted and reflected by the beamsplitter.

19. Apparatus in accordance with any one of claims 3 to 18, characterised in that; the concave mirror (503) is spherical or aspherical.

20. Apparatus in accordance with any one of claims 3 to 19, characterised in that; the concave mirror (513) has one refracting surface and one reflecting surface.

21. Apparatus in accordance with any one of claims 3 to 18, characterised in that; the concave mirror (503) is provided by a lens/mirror array.

22. Apparatus in accordance with any one of claims 3 to 21, characterised in that; it further comprises a moulded frame on to which the screen (501), beamsplitter (502,508), concave mirror (503), fold mirrors (510) and magnifying optics (505) are mounted so as to be accurately relatively positioned.

23. A head mounted display apparatus in accordance with claim 1, characterised in that; monocular magnifying optics (2,3,4) are disposed optically ahead of said screen (1) and are adapted to magnify a complete image received therefrom, said offset beamsplitter (5) is adapted to divide images received from said magnifying optics into first and second optical paths, and corresponding to each of said optical paths an associated plurality of reflective surfaces (15,16,17,18) including one concave mirror surface (18) with said plurality of reflective surfaces being collectively adapted to permit the viewing at the associated left or right exit pupil (10) of a respective image received from the offset beamsplitter (5) at infinity focus, with the arrangement providing that said first and second mirrored surfaces (8,9) each correspond respectively to said first or said second optical path and with said first mirrored surface being offset to one side of the optical axis of the magnifying optics and said second mirrored surface being offset to the opposite side of said optical axis and further providing that the magnifying optics effect distortion of said video image to compensate aberrations induced by said concave mirror surface.

24. Apparatus in accordance with claim 23, characterised in that; said first and second mirrored surfaces (8,9) of the beamsplitter (5) are mutually substantially perpendicular planar surfaces with each said planar surface being generally upright.

25. Apparatus in accordance with claim 23 or claim 24, characterised in that; said display screen (1) is disposed in a generally horizontal plane and has a generally upright optical axis, the optical axis (X-X) of said magnifying optics (2,3,4) is generally horizontal, and a planar mirror inclined relative to both the horizontal and vertical is disposed intermediate said display screen and said magnifying optics to deflect the path of the display screen optical axis so that

after reflection from said planar mirror it extends generally coincident with the magnifying optics optical axis.

26. Apparatus in accordance with any one of claims 23 to 25, characterised in that; each associated plurality of reflective surfaces includes in addition to the concave mirror (18) a first plane mirror (15) that reflects the image from the offset beamsplitter (5) generally horizontally and rearwardly on to a second plane mirror (16) that reflects the image downwardly on to a reflective surface (17) of a planar semi-silvered beamsplitter (13) that reflects the image generally horizontally and forwardly on to said concave mirrored surface (18) which then collimates said image by reflection through the planar semi-silvered beamsplitter (13) so that it can be viewed at the associated left or right exit pupil (10).

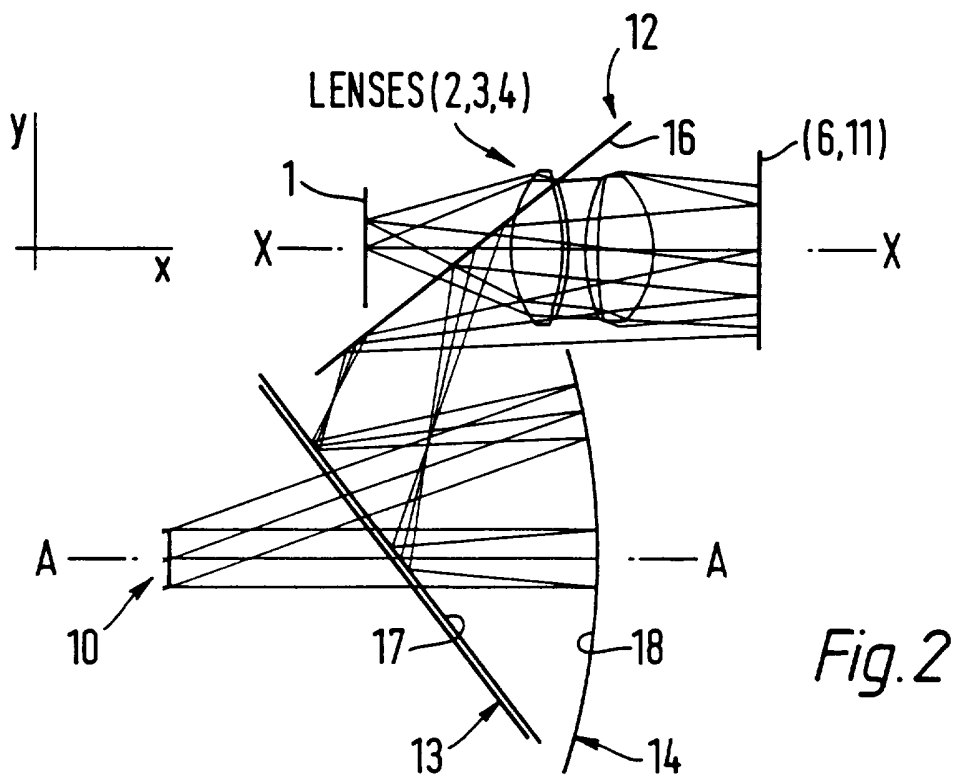
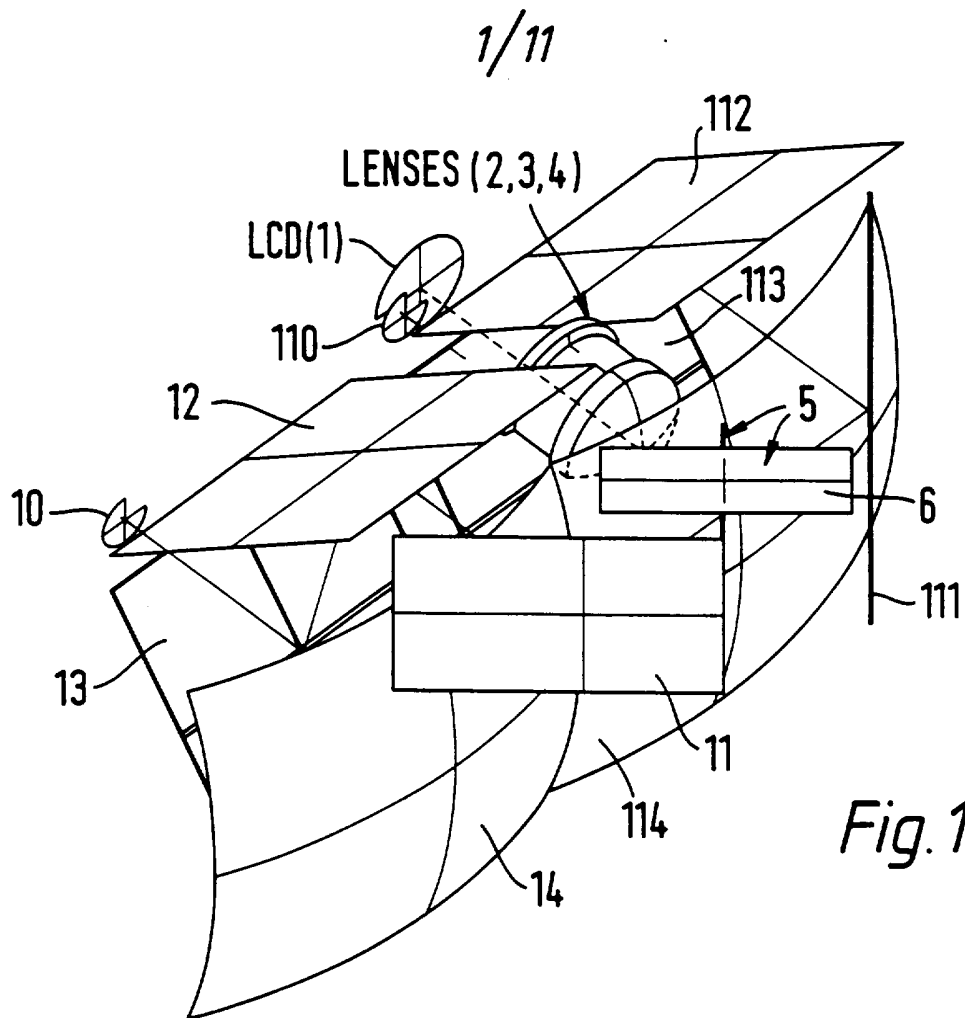
27. Apparatus in accordance with any one of claims 23 to 26, characterised in that; the display screen is a miniature LCD video screen (1).

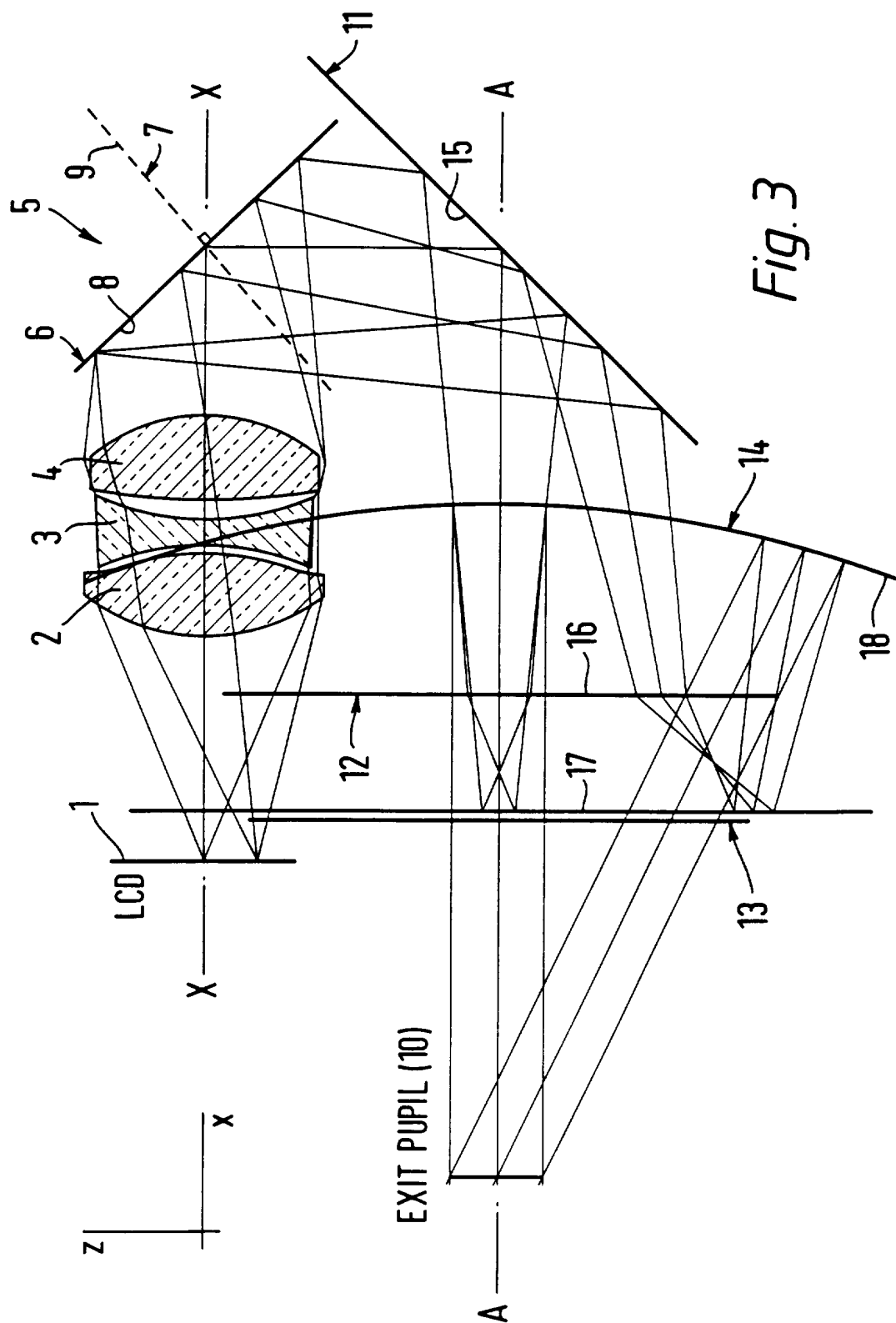
28. Apparatus in accordance with any one of claims 23 to 27, characterised in that; the magnifying optics (2,3,4) comprises at least one aspheric refracting surface.

29. Apparatus in accordance with any one of claims, 23 to 28 characterised in that; the magnifying optics comprises an array of three coaxially mounted lenses (2,3,4).

30. Apparatus in accordance with claim 29, characterised in that; the material composition of each of the three lenses (2,3,4) is chosen so that in combination chromatic aberration of a magnified image is minimised.

31. Apparatus in accordance with any one of claims 23 to 30, characterised in that; the magnified images can be viewed in binocular fashion substantially without parallax in a central field of view.





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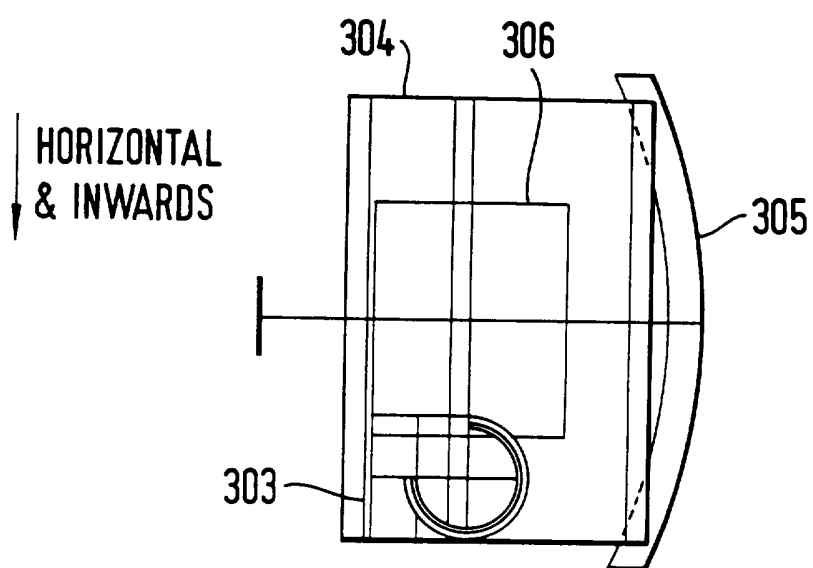
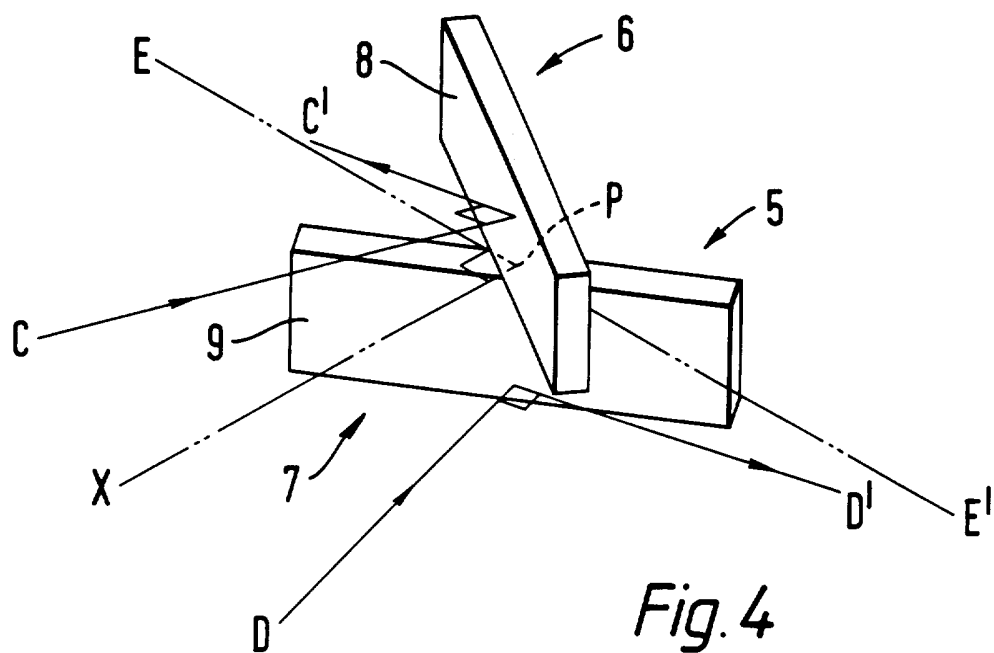
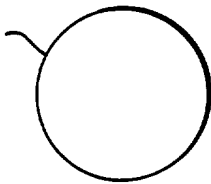


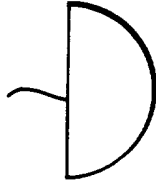
Fig. 6(a)

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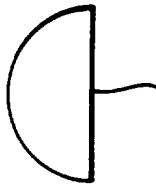
NOMINAL CIRCULAR EXIT PUPIL
BEFORE BEAMSPLITTING (20)



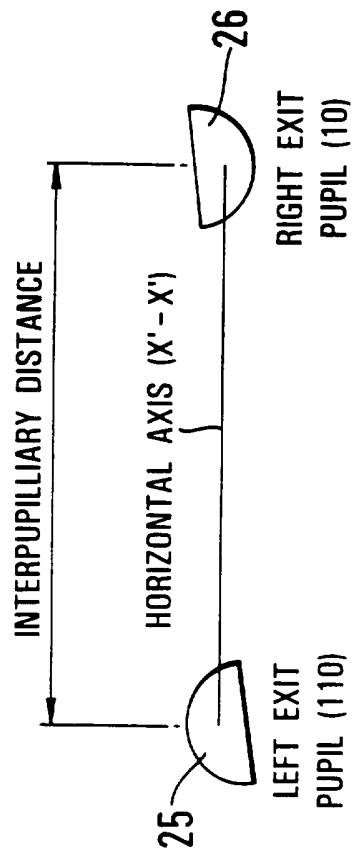
RIGHT EXIT PUPIL AFTER
BEAMSPLITTING (22)



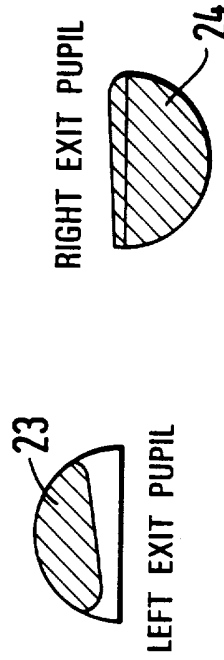
LEFT EXIT PUPIL AFTER
BEAMSPLITTING (21)



RELATIVE EXIT PUPIL POSITIONS:



TYPICAL VIGNETTED EXIT PUPILS ON
VIEWING A VERTICAL FIELD ANGLE:



KEY:



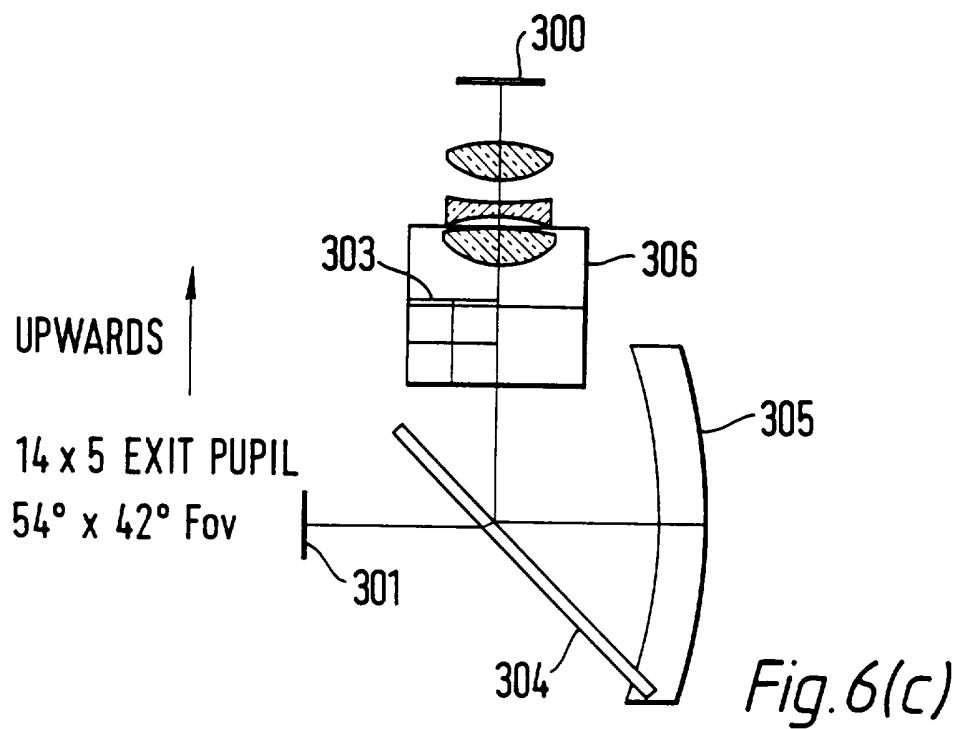
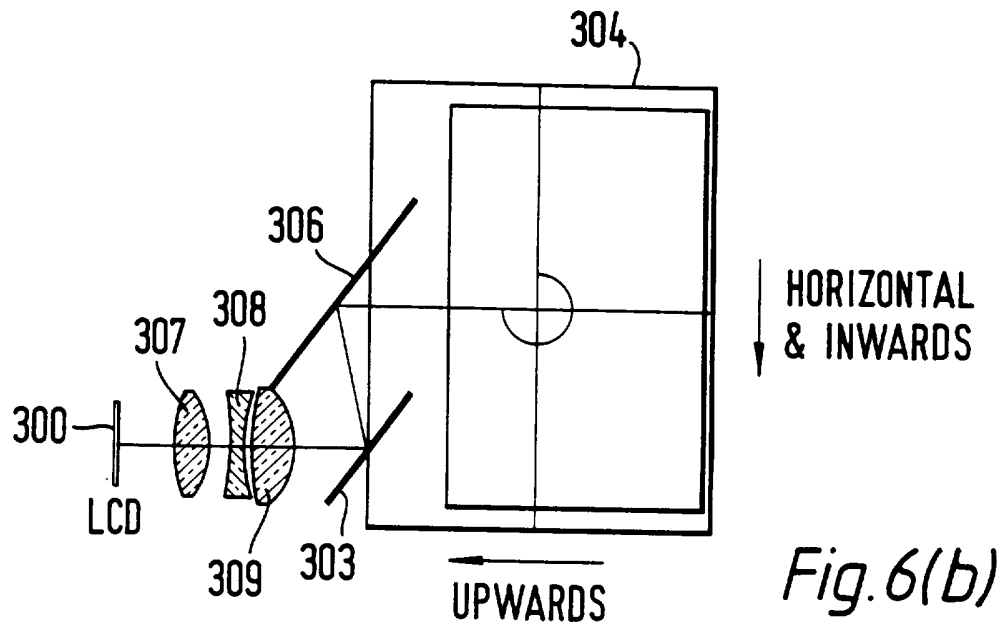
ON AXIS SHAPE



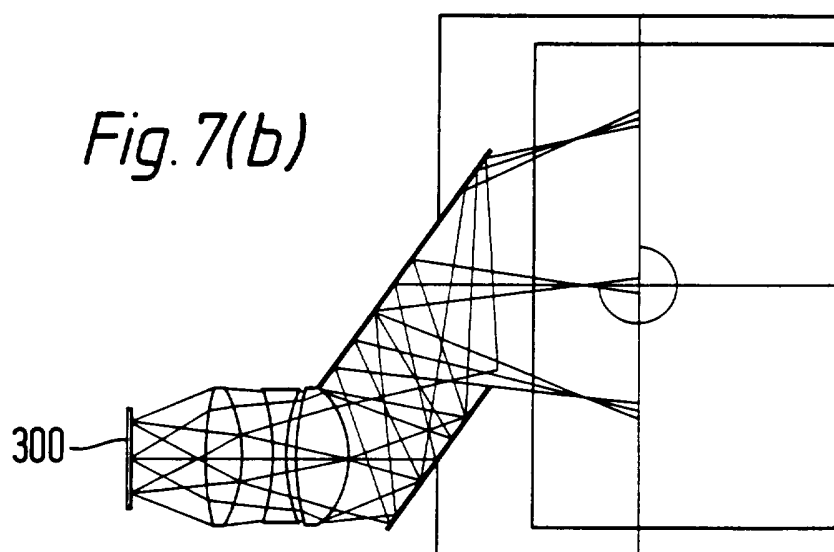
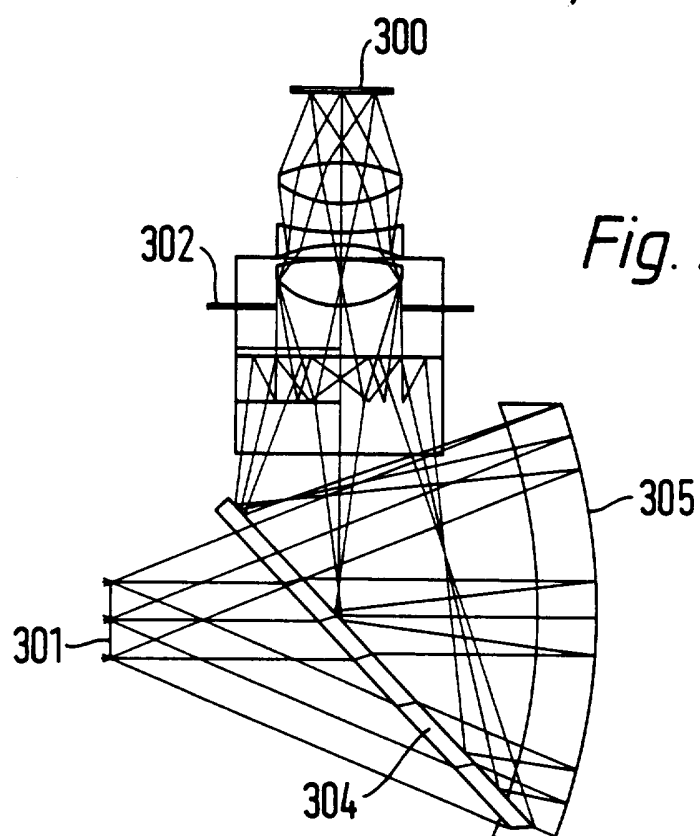
VIGNETTED SHAPE

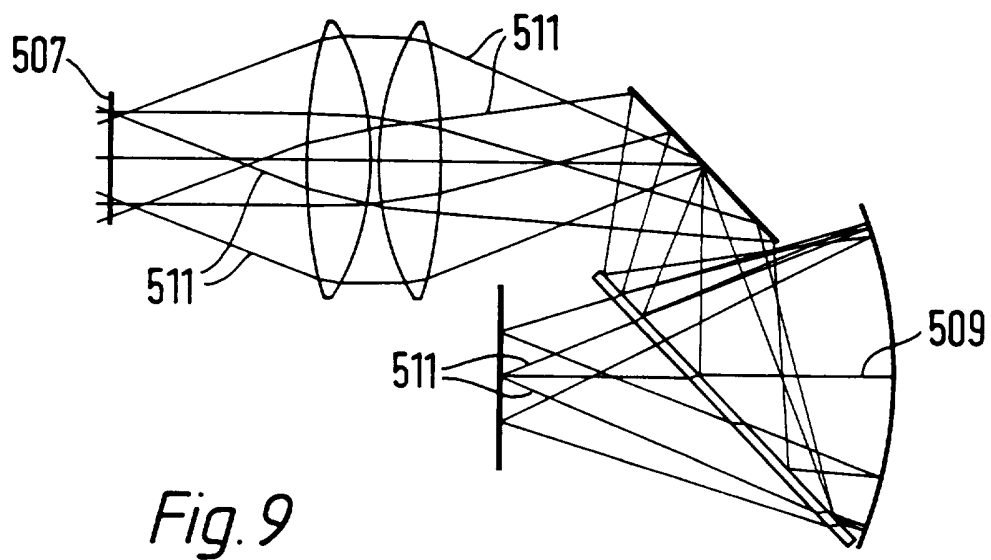
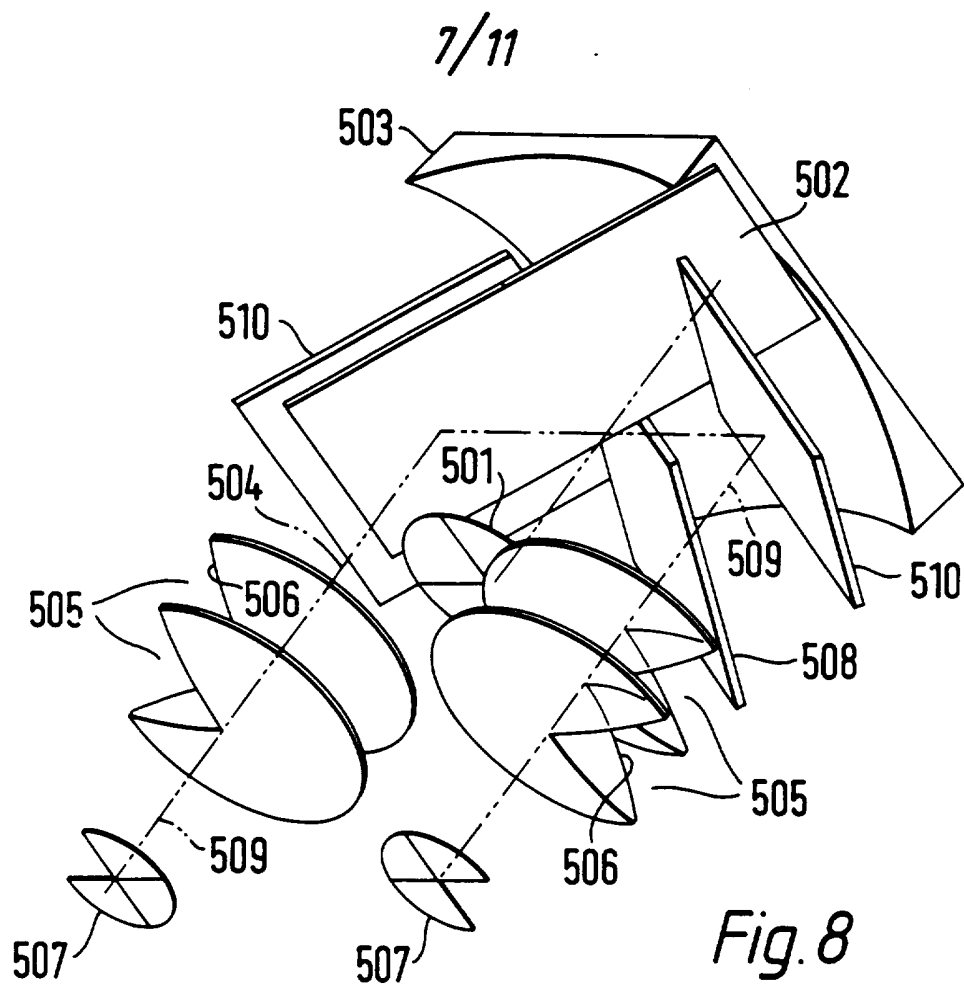
Fig. 5

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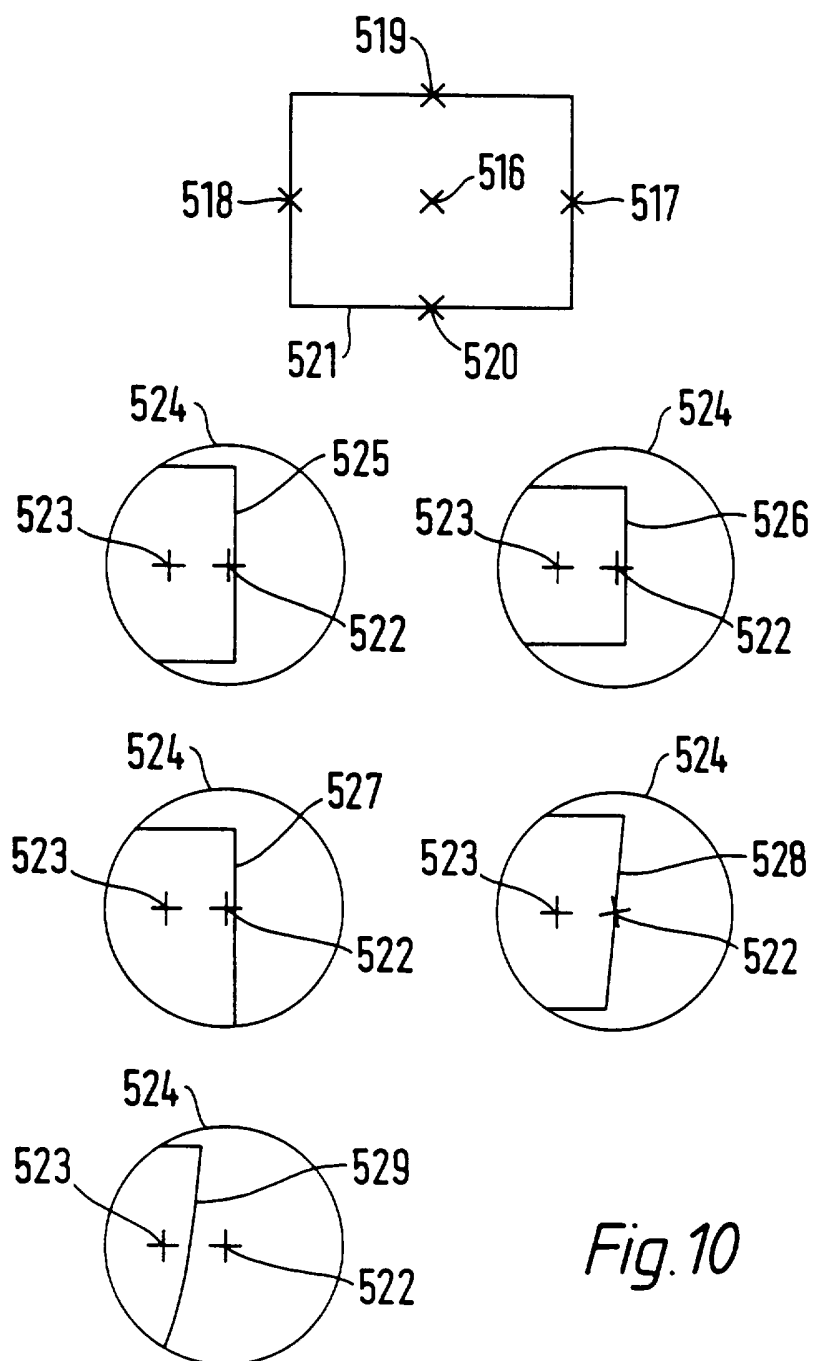


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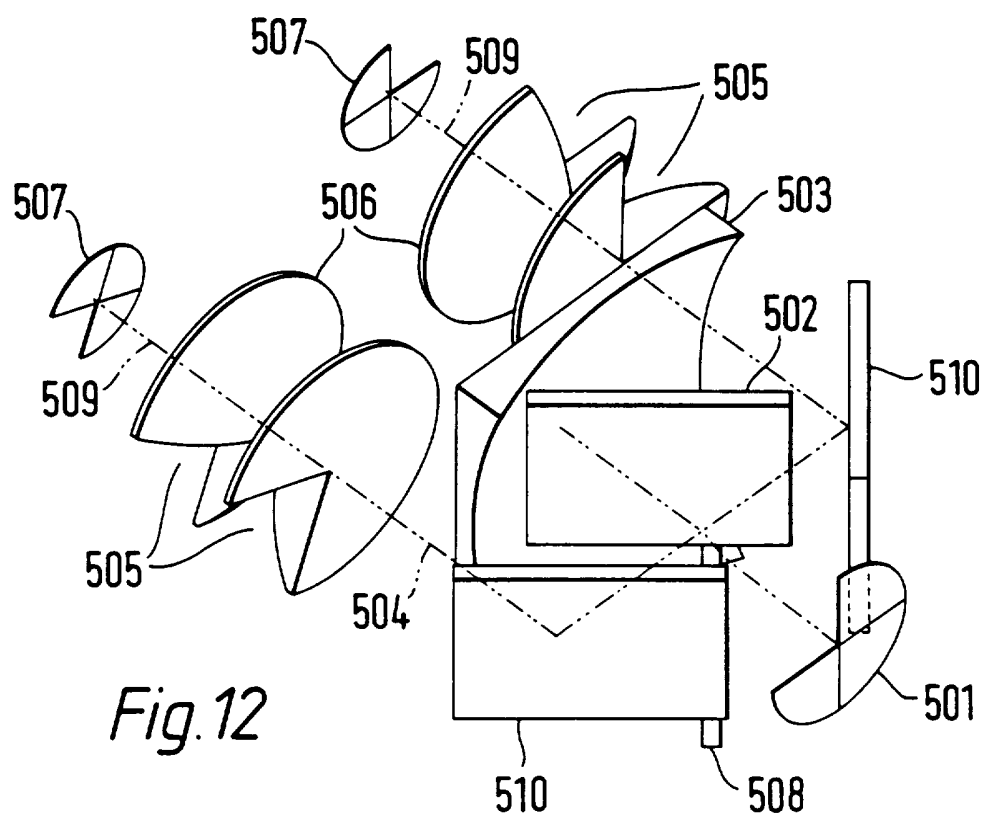
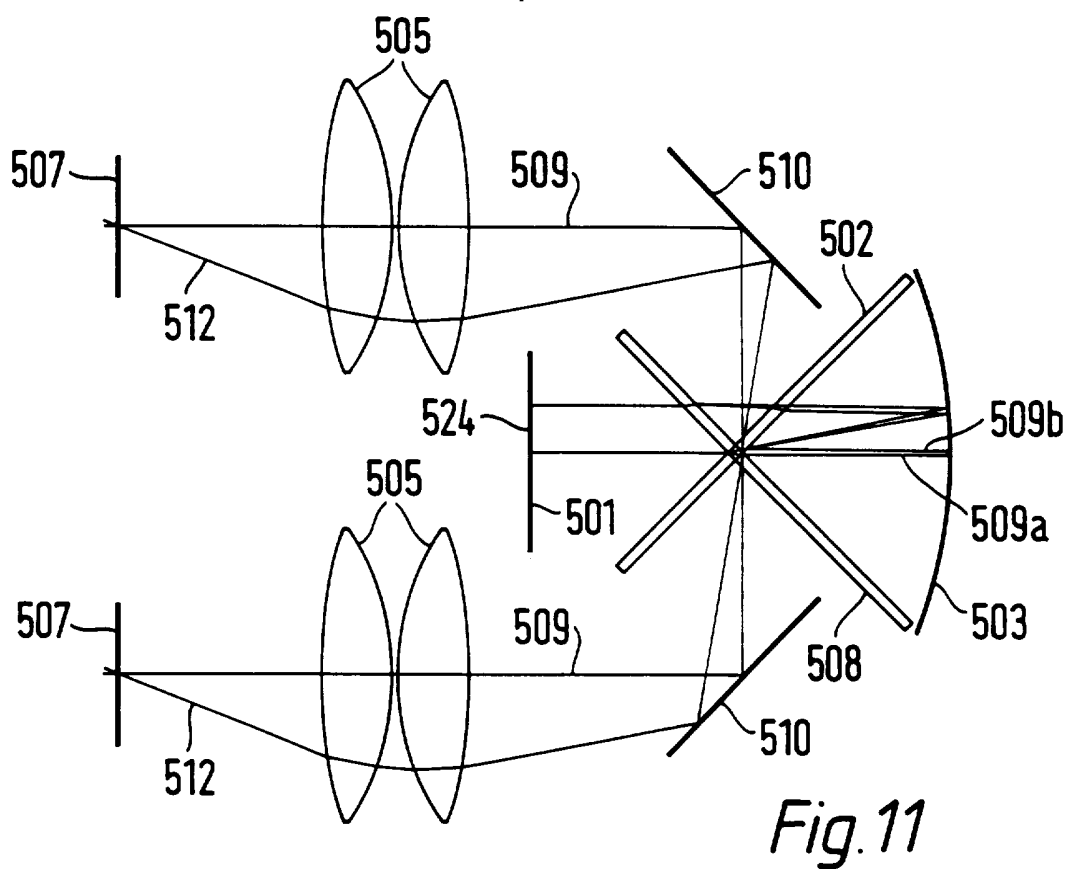




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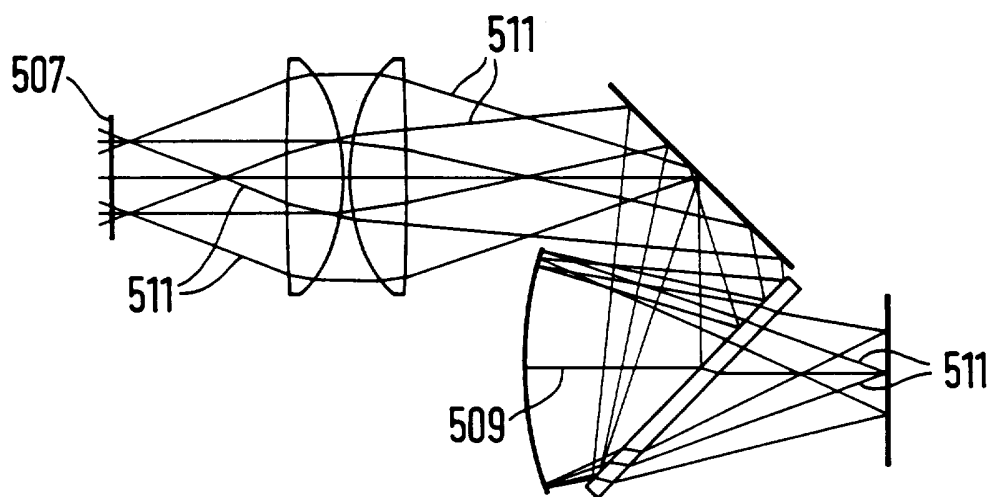


Fig. 13

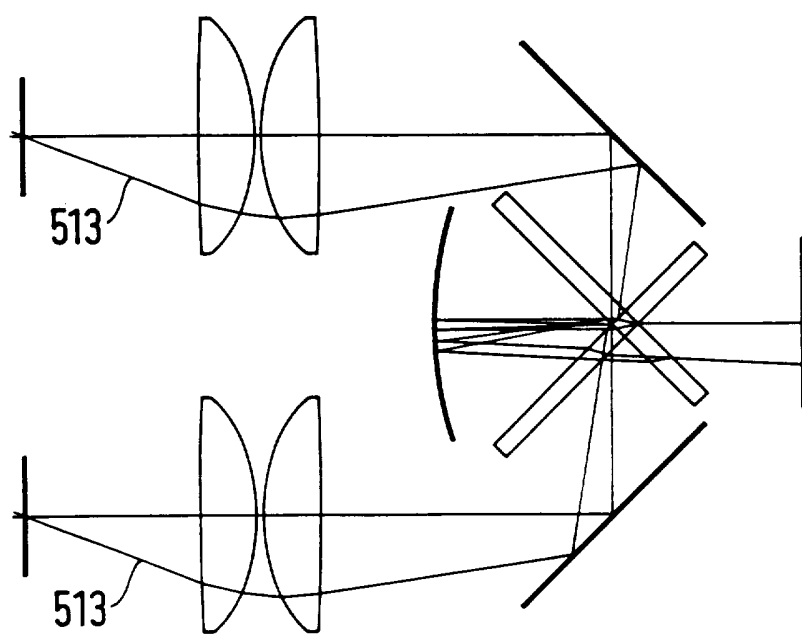


Fig. 14

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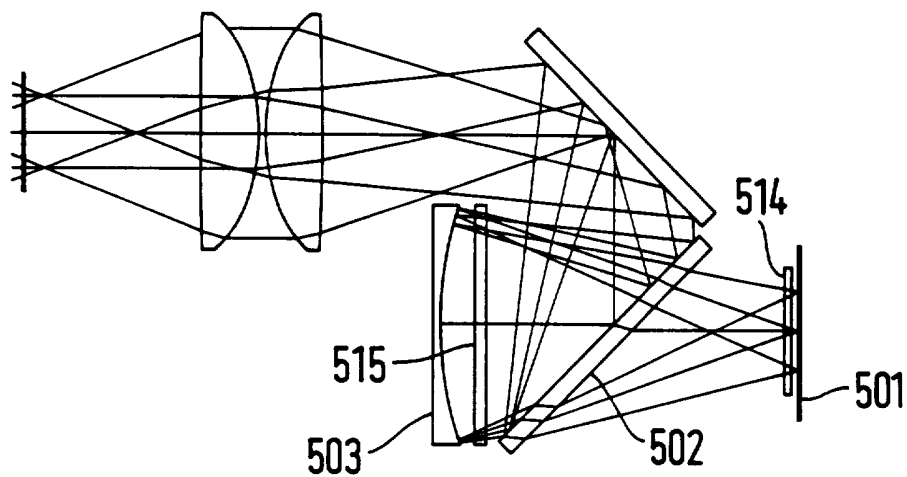


Fig. 15

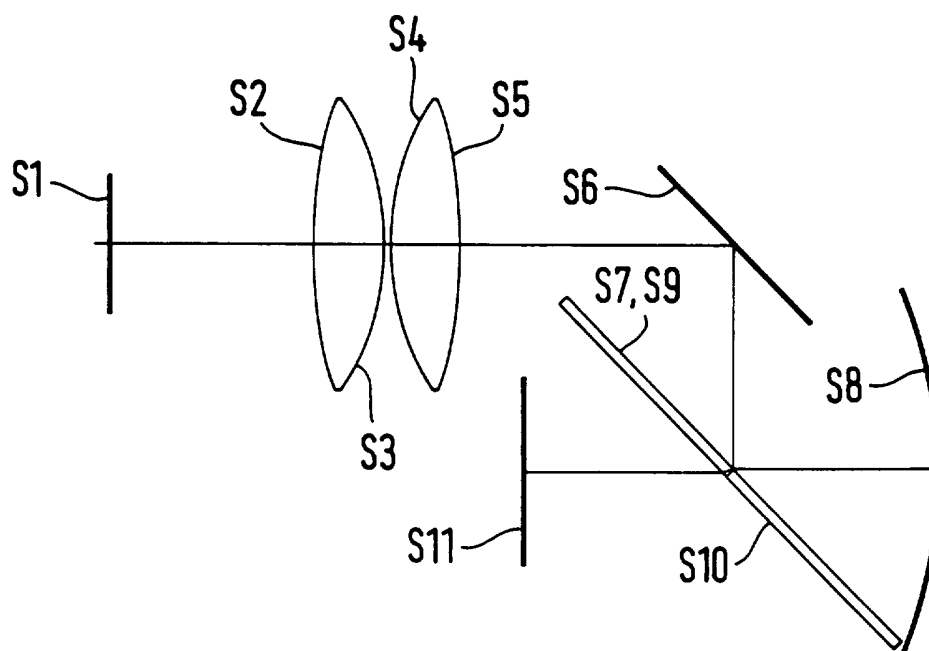


Fig. 16

INTERNATIONAL SEARCH REPORT

Inter - national Application No

PCT/GB 95/01891

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 G02B27/01

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6 G02B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y A	WO,A,85 04961 (HUGHES AIRCRAFT) 7 November 1985 see abstract see page 9, line 5 - line 22; figures see page 10, line 12 - line 32; claims 8,10 ---	1 3,4,23, 24
Y A	US,A,3 867 633 (PATRICK) 18 February 1975 see column 8, line 5 - line 13; figure 11 ---	1 3,23
A	WO,A,94 01798 (BANBURY) 20 January 1994 see page 5, line 1 - line 9; figure 7 see page 9, line 18 - line 30 ---	3,5
	-/--	

☒ Further documents are listed in the continuation of box C.

☒ Patent family members are listed in annex.

* Special categories of cited documents :

- *A* document defining the general state of the art which is not considered to be of particular relevance
- *E* earlier document but published on or after the international filing date
- *L* document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
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- *P* document published prior to the international filing date but later than the priority date claimed

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X document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

Y document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

& document member of the same patent family

Date of the actual completion of the international search

29 December 1995

Date of mailing of the international search report

10.01.96

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Authorized officer

Soulaire, D

INTERNATIONAL SEARCH REPORT

International Application No
PCT/GB 95/01891

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT		
Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US,A,3 923 370 (MOSTROM) 2 December 1975 see column 1, line 61 - column 2, line 39 see column 3, line 23 - line 59; figure 1 see column 4, line 44 - line 48 ---	23
A	EP,A,0 592 318 (SONY) 13 April 1994 see column 7, line 5 - line 21; figures 7,10 ---	3,5,25
A	EP,A,0 539 907 (KABUSHIKI KAISHA SEGA) 5 May 1993 cited in the application see column 5, line 1 - line 32; figures 3-6 see column 8, line 47 - line 50; figure 7 see column 9, line 25 - column 10, line 28; figure 11 ---	1,2
A	US,A,5 050 966 (BERMAN) 24 September 1991 cited in the application see figure 8 -----	1

INTERNATIONAL SEARCH REPORT

Information on patent family members

International Application No

PCT/GB 95/01891

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