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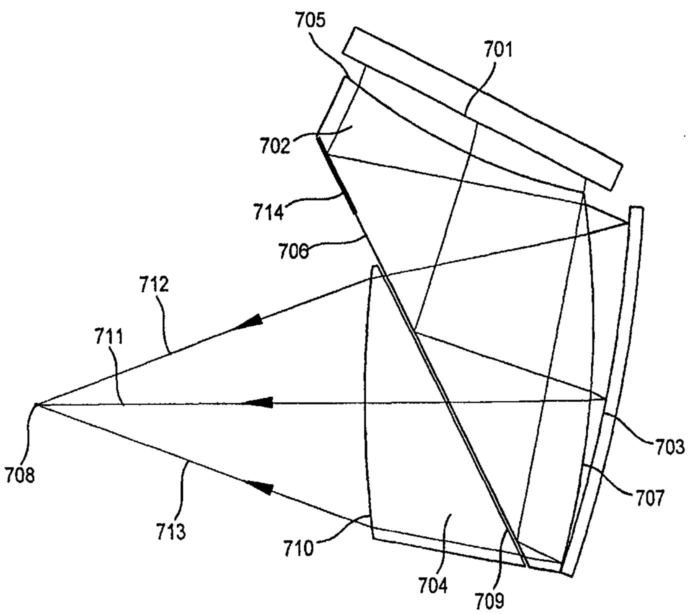

(57) Abstract

An imaging system to accept an input image from an image source (701) and provide an output image, the system comprising: a refracting block (702) having first, second and third optical surfaces; a concave mirror surface (703) outside the third optical surface of said block; and an optical path (711, 712, 713) from an optical input to an optical output of the system; the optical path including transmission through the first optical surface, internal reflection at the second optical surface, reflection at the concave mirror surface and transmission through the second optical surface.

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DISPLAY SYSTEM

The invention relates to design and construction of optical systems, and particularly with optical systems for display and formation of optical images. The invention will be particularly useful in design and construction of visual display systems.

Visual display systems are used in many applications, including: viewing of photographic slides, viewing of images from low-light-level and infrared cameras, presentation of computer-generated images, and presentation of weapon sights and symbology. Users of displays include aircraft pilots, firefighters, surgeons, maintenance engineers and players of virtual reality games.

Visual display systems may be considered generally to include two main parts: the display source and the display optics. The display source may be a simple passive component to be viewed, like a photographic slide. It may alternatively be a video-image source, such as a cathode ray tube (CRT), a liquid crystal display (LCD) with a suitable illuminator, or an electro-luminescent display (ELD). The essential functions of the display optics are to receive light from the display source and present the image to the user so that it appears to be at an appropriate distance from the user, and so that the user sees the display filling an appropriate angular field of view. To take one example, firefighters use helmet-mounted display systems to find their way through thick smoke, in which they can see nothing without the aid of an infrared camera. In the most convenient arrangement – leaving their hands free for vital tasks – the camera, the display source and the display optics may all be mounted on the firefighter's helmet or a head harness.

The requirements for visual displays include a minimum eye-relief and a minimum pupil area. The pupil area is the area in which the user's eye or eyes must be placed in order to see the display. Eye relief means separation of the pupil from the optics, which in some cases should include a clearance for a user's eyeglasses and/or facemask, depending on details of the display application. There are also in general requirements for minimum angular resolution, angular field of view and optics transmission. It may be required to present a display to one or both of the user's eyes. If both eyes receive an image, there are varying requirements on the overlap of the images presented to the two eyes, called a biocular field. Where there is a significant biocular field, there are requirements on alignment of the two images; misalignments of the images presented to two eyes are called binocular disparity. There is a very wide range of display requirements, these depending on the details of the applications.

We will describe systems aimed at providing advantages in design and construction of visual display systems, include capabilities to provide large eye relief and large pupil areas, with large field angles. Field angles are typically 60° x 40°, with eye relief of several centimetres. Pupil areas are typically 20mm diameter per eye, with some examples capable of providing an image to both eyes simultaneously from a single display source. Preferably, the arrangement can be made at low cost. This combination of design parameters will be of particular value in displays for firefighters.

In this document, example optical systems are generally described in operation as visual display systems, receiving light from display sources and providing visible images of the source at distances suitable for viewing by eyes. However, the optical systems may also be used with other sources of light, and with electro-magnetic radiation generally, including ultra-violet and infrared radiation.

The optical systems may also be used with radiation paths reversed, receiving radiation from distant sources and forming images on suitable targets. For example, the large field angles and large pupil areas provided by the examples described here will be of value in design and construction of imagers for wide-angle thermal infrared cameras. The separation of the pupil from the optics (which is eye-relief in a visual display application) may be used to allow a scanning mirror to be located at the pupil of an infrared imager.

Some of the designs described herein include a concave mirror that is tilted, so that the mean angle of incidence of useful light, or other radiation, is not normal to the mirror. Concave mirrors have been used previously in display optical systems and other imaging systems, with and without flat beam splitters, as indicated in figures 1 and 2. Concave mirrors have a basic advantage of low weight, in comparison with conventional refracting lenses. They also have low optical aberrations in comparison with all refracting elements, including Fresnel and gradient-index lenses, and in comparison with diffractive elements. Low aberrations are important in achievement of good angular resolution in display systems and other optical systems.

Figure 1 shows a design form frequently used in military helmet-mounted display systems. In this design, light from a display source 101, which is typically a CRT, is received by a relay lens 102 which relays an image of the source to the surface in space indicated in the diagram by the dashed line 103. The lines 104 and 105 indicate light rays from different points on the source, and include arrows to indicate direction. The beam is then reflected at the flat beam-splitter 106 onto the concave tilted mirror 107. The surface 103 is located at the nominal focal surface of the concave mirror 107, seen in reflection in the flat beam-splitter 106, so that the beam reflected from the concave mirror is collimated (i.e. the image of the source in the reflected beam appears to be at infinity). The collimated beam then passes through the flat beam splitter to the user's eyepoint 108.

Figure 2 shows a simpler arrangement, comprising a display source 201, a flat beam-splitter 202 and a concave mirror 203. In this case, light from the display source 201 passes directly to the beam splitter 202, which again reflects the light to the concave mirror 203. Here the display source itself is located approximately at the focal surface of the concave mirror 203, seen in reflection in the flat beam-splitter 202, so that the beam reflected from the concave mirror is approximately collimated. The collimated beam again passes through the beam-splitter to the user's eye, 204. In figure 2, the paths of light rays are indicated by the lines 205 and 206.

The system shown in figure 2 is very simple, but has a limited field angle capability in arrangements that give acceptable eye relief. The length of the light path from the source 201 to the base of the concave mirror 203, along the ray 206, must be approximately equal to the focal length of the concave mirror 203, for the light to be collimated by the mirror 203. But this light path is greater than the unobstructed height of the concave mirror 203. The maximum clear height of the concave mirror 203 is therefore less than its focal length. The focal length of the mirror 203 is equal to half of its radius of curvature. Therefore, if the eye point 204 is placed at the centre of curvature of the mirror 203, the angular subtense of the mirror at the eye point, which is equal to the vertical field angle, cannot be greater than 30°. A larger vertical field angle can be achieved by bringing the eye point 204 closer to the beam splitter 202, but this reduces the eye relief provided by the system. It also degrades the resolution of the optical system, which works best when the pupil is at the centre of curvature of the concave mirror 203. The field angle provided by the arrangement is therefore typically about 30°, which is undesirably small for some applications.

This problem of limited vertical field angle, in the simple arrangement of figure 2, is resolved in the more complex arrangement of figure 1 by addition of the projection lens 102. The lens 102 relays a real image of the display source 101 to the surface 103. This allows the display source itself to be remote from the concave mirror 107, so the source does not limit the unobstructed height of the concave mirror 107, as viewed from the eye point 108.

The systems shown in figures 1 and 2 both suffer potentially from low efficiency in transmission of display brightness to the user, since some light is lost at both the reflection and transmission through the beam-splitter, 106 or 202, (by stray transmission and stray reflection respectively). If the beam-splitter is designed to reflect 50% and transmit 50%, the system will have a maximum theoretical overall transmission of 25%. The more complex system shown in figure 1 is capable of better efficiency because the concave mirror 107 is tilted. This arrangement is often designed such that the first angles of incidence on the beam-splitter element 106 are larger than the second angles of incidence on the same element, as indicated in the diagram. Special coatings are sometimes used for the beam-splitters of such systems, that provide relatively high reflection at high angles of incidence and relatively high transmission at smaller angles of incidence. Using difference of angles of incidence, it is possible to achieve overall transmission efficiencies well above 25% for selected wavelengths. However, the beam-splitter coatings required are expensive, and the maximum efficiency is still relatively limited.

The system shown in figure 1 is commonly used in military helmet-mounted display systems, but has some disadvantages, particularly for use in low-cost displays and other optical systems. In particular, addition of the projection lens 102 adds to system complexity. The projection lens 102 also limits the effective pupil area of the optical system at the eyepoint 108, since the pupil of the projection lens is imaged onto the eyepoint by the concave mirror 107. Thus a large pupil requires a large projection lens 102. Systems of this kind therefore tend to be complex and expensive. Cost is also increased if complex coatings are used on the beam splitter to improve transmission of display brightness.

Display optical designs are also known in which a concave mirror is used without a beam-splitter, as indicated in figure 3, which gives an advantage in improved transmission without expensive coatings. In this case, light from a display source 301 falls directly onto the tilted concave mirror 302, which approximately collimates the light reflected towards the eyepoint 303. In figure 3, the paths of light rays are indicated by the lines 304 and 305. It is necessary for the user to view the mirror 302 past the edge 306 of the display source 301. The display source 301 must therefore be substantially offset from the user's line of sight. For a given display field angle, this requires that the mirror 302 shall be tilted through a relatively large angle, compared with the tilts required for the mirrors 107 and 203 in the design forms shown in figures 1 and 2.

The tilt of the mirror 302 introduces relatively large optical aberrations. The aberrations blur the image, limiting resolution, and, in biocular systems the aberrations also introduce binocular disparity. The aberrations can be reduced by using mirrors with long radii of curvature, and/or by limiting the field angles of the display in order to limit the required mirror tilt. This leads to designs that are too large and too limited in field angle, for successful application in most visual display applications. (However, the design form has been used very successfully in displays for flight simulation, using mirrors with radii of curvature typically in the region 3 metres.)

Optical systems for display applications in which the concave mirror is formed on one surface of a solid block of refracting material are also known, from US patents numbers 5,701,202 and 5,745,295.

Figure 4 shows an optical design including a display source 401, which may be an LCD, and a refracting block 402. The block 402 has three optical surfaces, 403, 404, and 405. The third optical surface, 405, carries a mirror coating. The paths of light rays travelling from the source 401 to the user's eye at point 406, are indicated by the arrowed lines 407, 408, 409 and 410. The light from the source 401 enters the block 402 through the top refracting surface 403. The light is then internally reflected at the surface 404 and falls on the mirror-coated face 405. The light reflected from the mirror-coated face 405 emerges from the block by refraction through the surface 404, and is directed towards the user's eye at point 406.

Each ray has two angles of incidence on surface 404, a first angle of incidence when the light first hits the surface, and a second angle of incidence when the light returns to the surface after reflection form surface 405. The mirror-coated surface 405 is tilted so that the second angles of incidence of the rays on surface 404 are smaller than the first angles of incidence on surface 404. For part of surface 404, the first angles of incidence of rays are above the critical angle, so that the light cannot emerge and the light is totally internally reflected. The rays return to this part of surface 404, with angles of incidence below the critical angle, so that the rays are refracted out of the block 402. Some light will be lost by absorption at the mirror, and by scatter at all optical surfaces, but the optical system can in principle give transmission over 90%.

Part of the area of surface 404, indicated by the heavy line 412, that is not required to transmit light, may be mirror-coated. It is not essential for this area to be totally-internally reflecting, so that the system may be designed such that the first angles of incidence in the area 412 are not above the critical angle. In this case, mirror coating of the area 412 is required to ensure efficient internal reflection. The opaque mirror coating may also have a function in blocking stray light from the source to the eye.

Light from each point on the source surface, is approximately collimated by the mirror surface 405, which is concave on the side which reflects display light. This is indicated for example by the light from the point 411 at the source, indicated by the rays 407 and 408. The rays diverge until they reach the concave mirror surface 405, and are reflected nearly parallel to each other and the rays also emerge nearly parallel from surface 404. In practice, the system will be adjusted such that there is a slight divergence of such rays emerging from the block 402 towards the user's eye, so that the image of the source will appear at a finite distance away from the eye.

Advantages of optical systems like that shown in figure 4, in which an internally-reflecting block of refracting material 402 is introduced between the concave mirror surface 405 and the observer's eye point 406, will now be explained by comparison with the arrangement of figure 2, in which there is no substantial volume of refracting material.

In both the system of figure 2 and the arrangement of figure 4, light from a source – 201 in figure 2 and 401 in figure 4 – falls first on a near-flat reflecting surface – 202 in figure 2 and 404 in figure 4. In both cases the beam then falls on a concave mirror – 203 in figure 2 and 405 in figure 4 – which collimates the light and projects it towards the user's eye, at points 204 and 406. In both cases a maximum field angle is achieved, in the plane of the diagram, when the source, 201 or 401, is brought as close as possible to the top of the concave mirror, 203 or 405. The two systems therefore produce similar maximum field angles in the beam immediately after reflection at the concave mirror, 203 or 405, indicated by the angle between rays 205 and 206 in figure 2 and the angle between rays 409 and 410 in figure 4. This field angle is unchanged by transmission of rays 205 and 206 through the beam-splitter 202 in figure 2. In contrast, the angle between extreme rays 409 and 410 in figure 4 is increased by refraction at surface 404, before the rays reach the eye point 406.

Use of an internally-reflecting block of refracting material, 402 in figure 4, between the concave mirror surface, 405 and the eye point 406 therefore increases the field angles that can be achieved. The improvement in field angle is, in simple theory, approximately proportional to the refractive index of the material of the block 402. In practice, it is possible to achieve a field angle, in the plane of the diagram, of over 40°. This is achieved without introducing a relay optical system, as illustrated by the relay lens 102 in figure 1.

A second advantage of the internally-reflecting block, 402 in figure 4, is that it provides optical systems of higher efficiency, in terms of transmission of display brightness. In the arrangement of figure 2 and in the arrangement of figure 4, it is necessary for an optical surface – a surface of 202 in figure 2 and surface 404 of figure 4 – to both reflect and transmit useful light, over part of each of their areas. In the case of the arrangement in figure 4, the part of surface 404 that is required to transmit reflects by total internal reflection, so that it does not require a coating to enhance reflection. On the contrary, this part of surface 404 can reasonably be uncoated or anti-reflection coated, and in these cases it will have close to 100% internal reflectance. By contrast, element 202 of figure 2 does not provide total internal reflection over any part of its surface area, so that the element cannot easily provide high efficiency in both reflection and transmission. It may for example be coated to provide approximately 50% reflection and 50% transmission, so that the overall efficiency for transmission of display brightness will not exceed 25%.

Optical design data for the system shown in figure 4 is presented in Table 4-1. In this table, the optical surfaces are listed in reverse optical order from the eye-point 406 back to the display 401, using the same numerals in the table as in figure 4. Separations, radii of curvature and shifts of optical surfaces are given in millimetres, and tilts of surfaces in degrees. All three surfaces of the block – surfaces 405, 404 and 403 – are toric. Toric surfaces are circular in any section, but the radius of curvature varies between extreme values in the horizontal and vertical sections. The table therefore gives two radii of curvature for all surfaces, except for the display, which illustratively is flat (although it may be curved), and the eye point. The convention is that positive radii of curvature indicate that the centre of curvature is on the right side of surface, with light travelling left to right. Separations are measured between neighbouring surfaces in the left-to-right direction. Shifts of surfaces are in the direction orthogonal to the left-right axis, in the plane of the diagram figure 4.

Table 4-1 Design data for system of Figure 4

Surface	Radius-vertical (mm)	Radius - horizontal (mm)	Separation (mm)	Material	Tilt, degrees	Vertical shift (mm)
Eye point, 406						
			80	Air		
404	8123	2710			17.0	---
			25	PMM		
405	-188	-174			-12.5	---
			-25	PMM		
404	8123	2710			17.0	---
			3	PMM		
403	175	495			71	50
			11.7	Air		
401 (source)		flat			44	59

The optical system shown in figure 4 is a display optical system optimised for a single eye, so that two such systems would be required for a biocular display. The system gives good resolution for an angular field of view 40° high x 60° wide. Correction of the optical design for image-blurring aberrations is improved by allowing the surfaces 403 and 404, as well as the mirror surface 405, to be curved.

Use of refracting material between the two reflecting surfaces aids in correction for optical aberrations, by reducing the aberration known as field curvature, which produces a variation in focus across the image. This aberration is produced mainly by the converging power of the concave mirror. Introduction of refracting material can be considered as addition of a converging lens used in a double-pass. The converging refracting power introduces field curvature in the opposite sense to that of the concave mirror, and it also reduces the necessary curvature of the concave mirror surface.

However, the performance of the optical system shown in figure 4 is limited by optical aberrations, mainly astigmatism and coma, produced by the mirror surface 405. These aberrations are increased by the tilt of the surface 405, with respect to the useful incident and reflected beams. The tilt of surface 405 is essential for the angles of the useful rays on surface 404 to be different for internal reflection and transmission, and this difference of incidence angles on surface 404 is essential for the reflection of rays at the surface to be total-internal within the area of surface 404 that is required to transmit. Thus the aberration produced by the mirror surface 405 is linked to the aspect of the design that produces efficiency, and is difficult to avoid within the basic design concept.

Part of the aberration produced by tilt of the mirror surface 405 in figure 4 can be corrected by introducing curvatures in surfaces 403 and 404. However, the correction that can be achieved at surface 403 is limited mainly to field curvature and tilt of the image focal surface, because this surface is close to the source 401. Any substantial curvature of surface 404 produces aberration mainly by internal reflection (because the optical power of a surface is much higher in internal reflection than in transmission, for common refractive indices). But, in the reflected path surface 404 is strongly tilted with respect to the incident beam, so that it is much close to one side of the source than to the other. Curvature of surface 404 therefore tends to produce aberration that is very non-uniform across the image field. Therefore little useful correction is feasible at surface 404 also.

Optical aberrations produced by the tilted surface 405 in figure 4 can alternatively be partially corrected by insertion of a lens element between the block 402 and the eye point 406. The aberration correction that can be achieved is again limited in practice, mainly because the lens and the mirror 405 cannot easily be placed near a common optical axis, without seriously reducing the eye relief provided by the system. However an added lens can reduce the necessary curvature of the mirror, which tends to reduce its optical aberrations.

An optical system of the kind illustrated in figure 4, appears to be suitable, in practical head-mounted display systems, for providing an image to one eye of a user. Two such optical systems, with two display sources, are generally required to provide a display to both of a user's eye simultaneously. However, the main problem, in using such systems to provide an image to both eyes from a single display source, is that the aberrations of the optical system introduce too much binocular disparity, unless the optics are made excessively large for mounting on a helmet or on the user's head.

There are significant advantages in providing a display to both eyes from a single display source, such as an LCD or ELD, via a single optical path. First, the display system can have lower cost and power requirements if it requires only one source, and the display optics are in some respects simplified if only one optical channel is needed. Second, binocular disparity due to misalignment of images on two display sources is avoided. Thirdly, the single optical system avoids a discontinuity at a meridian plane between the user's eyes, which allows the user a larger field to the left from his right eye, and to the right from his left eye. This increase in inward-looking fields for the two eyes is particularly important for display systems in which large eye relief is required since a meridian-plane discontinuity, of a system with two optical channels, extends further from the user's face when the optics are further away.

However, aberration correction for an optical system serving both of a user's eyes simultaneously presents much more serious problems than correction for one eye. The effective exit pupil diameter must be at least 70mm for two eyes, compared with 10mm to 20mm for one eye (depending on the application). Binocular disparity must also be closely controlled in design of a system that serves two eyes.

Described herein are new optical design forms that are suitable for wide-angle visual display systems having large eye relief and providing an image to both of a user's eyes from a single display source. The designs may also be used in other imaging optical systems that require corresponding capabilities.

The present invention provides an imaging system to accept an input image from an image source and provide an output image, the system comprising:

a refracting block having first, second and third optical surfaces; *characterised by* a concave mirror surface outside the third optical surface of said block;

an optical path extending from the image source to an optical output of the system; the optical path including transmission through the first optical surface, internal reflection at the second optical surface, reflection at the concave mirror surface and transmission through the second optical surface.

The present invention also provides A method of providing an enhanced field of view for a display system,

the method comprising:

providing a retracting block, said block including a transmitting surface and a reflecting surface;

providing an image source;

characterised by

providing a concave mirror with a focal length comparable to an effective lateral dimension of the mirror;

providing the image source adjacent the mirror;

providing the refracting block in front of a reflecting surface of said mirror extending substantially across said lateral dimension of the mirror;

directing light from the image source into the block and, via the reflecting surface, onto the concave mirror; and

directing light from the concave mirror through the transmitting surface of said block to provide a user image, whereby said field of view of the user image is enhanced.

In the preferred arrangement any or all of the optical surfaces of the block may be curved to aid in correction of optical aberrations in the source image formed by the block and the concave mirror.

A refracting lens may be added to the optical assembly outside any of the three surfaces of the block, to further aid correction of optical aberrations in the image of the source formed by the block and the concave mirror.

It is to be understood that the term "light" is used for convenience to mean electromagnetic radiation that may be ultraviolet, visible or infrared.

In the arrangements described, the light path may be reversed.

Where the invention is used in a display system, the source may be a display unit, such as a CRT, LCD or ELD. In this case, light leaving the second surface of the block is directed towards the user's eye or eyes, and the image of the source is formed at a suitable distance from the user, for example between 0.5m and infinity.

The material of the refracting block may be selected for good light transmission, and where possible for low density in order to minimise weight. Plastics materials, for example polymethyl methacrylate (PMM), polystyrene, cyclic olefin copolymer or polycarbonate may be used.

Preferably the system includes a concave reflecting mirror surface and a block of refracting material that provides one internal reflection, as in the design forms represented by figure 4. These features provide relatively large field angles and good transmission efficiency. However, in the preferred arrangement described below, the concave mirror is separate from the refracting block, and tilted with respect to the neighbouring block surface, whereas the concave reflecting surface of figure 4 is formed on one surface of the refracting block that also provides an internal reflection at another surface. The separation of the concave mirror surface from the refracting block is an important feature of the invention, allowing much improved correction for optical aberrations, as required particularly to provide a large exit pupil.

Preferred embodiments of the invention will now be described, by way of example only, with reference to figures 5, 6, 7 and 8 in which:

Figure 5 shows the optical design of an imaging system using a refracting block and a separate mirror;

Figure 6 shows an imaging system using a first optical design using a refracting block, a separate mirror, and a separate refracting lens element;

Figure 7 shows an imaging system using a second optical design using a refracting block, a separate mirror, and a separate refracting lens element,

Figure 8 shows an imaging system using a third optical design using a refracting block, a separate mirror, and a separate refracting element, and,

Figure 9 shows a firefighter's helmet with a display system in accordance with the invention mounted thereon.

Figure 5 shows an imaging system including a display source 501, a refracting block 502 and a concave mirror 503. The block 502 is made of PMM and has three optical surfaces, 504, 505 and 506. The paths of light rays travelling from the source 501 to the user's eye at point 507, are indicated by the arrowed lines 508, 509, 510 and 511. The light from the source 501 enters the block 502 through the top refracting surface 504. The light is then internally reflected at the surface 505 and leaves the block 502 at the surface 506. The light is reflected back into the block through surface 506 by the concave mirror 503. The light is refracted out of the block 502 at the surface 505, and is then directed towards the eye point 507.

Part of the area of surface 505, indicated by the heavy line 512, is mirror-coated to ensure internal reflection of light from this part of the surface. However, the reflection of light from the other part of surface 505 is total internal reflection, so that it is not necessary for this other part to carry a mirror coating. The light finally emerges from the block 502 through that part of surface 505 that is not mirror coated. Surfaces 504 and 506, and the part of surface 505 that is not mirror-coated, may be anti-reflection coated to improve transmission of the optical system.

The system shown in figure 5 retains the principal advantages of the simpler system of figure 4. Use of total internal reflection and transmission at surface 505, on successive incidences, allows high overall transmission of display light. The system is capable of providing relatively large field angles, due to use of refracting material in the light path between the display 501 and the main collimating surfaces 506 and 503, since the field angle produced by this configuration within the refracting block 502 is increased by refraction of light out of surface 505. The same advantages are retained in the systems described with reference to figure 6 and 7.

Light from each point on the source surface, is approximately collimated. In this case, collimation is produced mainly by the effects of surfaces 503 and 506. However, all surfaces can be curved to improve the correction of the design for optical aberrations. The design in figure 5 has an additional surface, in comparison with the design shown in figure 4. This allows improved correction for optical aberrations, so that the design is suitable to be used in a display system serving both of the user's eyes simultaneously. The design is optimised for a field 40° high x 60° wide and for two eye pupils with a nominal separation of 70mm. Correction for optical aberrations in this case includes correction for binocular disparity.

Optical design data for the system shown in figure 5 is presented in Table 5-1. The optical surfaces are listed in reverse optical order from the eye-point 507 back to the display 501, using the same numerals in the table as in figure 5. Separations, radii of curvature and shifts of optical surfaces are given in millimetres, and tilts of surfaces in degrees. All three surfaces of the block 502 – surfaces 504, 505 and 506, and the mirror surface 503 – are toric, so that the table gives two radii of curvature for these surfaces. The conventions of the table are the same as for Table 4-1.

Table 5-1 Design data for system of figure 5

Surface	Radius-vertical (mm)	Radius - horizontal (mm)	Separation (mm)	Material	Tilt, degrees	Vertical shift (mm)
Eye point, 507						
			80	Air		
505	-6539	-944			17.0	---
			30	PMM		
506	-188	-175			-8.5	---
			6.8	Air		
503	-231	-249			-18	---
			-6.8	Air		
506	-188	-175			-8.5	---
			-30	PMM		
505	-6539	-944			17	---
			8	PMM		
504	-292	880			71	73
			-2.1	Air		
501 (source)		flat			61	78

Figure 6 shows an imaging system including a display source 601, which may be a 4" LCD, a refracting block 602, a concave mirror 603 and refracting element 604. The block 602 is made of PMM and has three optical surfaces, 605, 606 and 607. The paths of light rays travelling from the source 601 to the user's eye at point 608, are indicated by the arrowed lines 609, 610, 611 and 612. The light from the source 601 enters the block 602 through the top refracting surface 605. The light is then internally reflected at the surface 606 and leaves the block 602 at the surface 607. The light is reflected back into the block through surface 607 by the concave mirror 603. The light is refracted out of the block 602 at the surface 606. The light then passes through the refracting element 604, which has optical surfaces 614 and 615, and is then directed towards the eye point 608.

Part of the area of surface 606, indicated by the heavy line 613, is mirror-coated to ensure internal reflection of light from this part of the surface. However, the reflection of light from the other part of surface 606 is total internal reflection, so that it is not necessary for this other part to carry a mirror coating. The light finally emerges from the block 602 through that part of surface 606 that is not mirror coated. Surfaces 605, 607, 614 and 615, and the part of surface 606 that is not mirror-coated, may be anti-reflection coated to improve transmission of the optical system.

Table 6-1 Design data for system of figure 6

Surface	Radius-vertical (mm)	Radius - horizontal (mm)	Separation (mm)	Material	Tilt, degrees	Vertical shift (mm)
Eye point, 608						
			70	Air		
615	-291	-88			0.7	---
			10	PMM		
614	-209	-135			17.1	---
			0.1	Air		
606	-65000	-65000			17.0	---
			28	PMM		
607	-176	-156			-10.3	---
			4.5	Air		
603	-248	-195			-19.1	---
			-4.5	Air		
607	-176	-156			-10.3	---
			-28	PMM		
606	-65000	-65000			17.0	---
			6	PMM		
605	-240	312			68	60
			4.6	Air		
601 (source)		flat			51	65

Light from each point on the source surface, is approximately collimated, collimation being produced in this case mainly by the effects of surfaces 603 and 607. However, all surfaces can be curved to improve the correction of the design for optical aberrations.

The design in figure 6 has an additional element, 604, in comparison with the design shown in figure 5. The principal function of the additional element 604 is to improve control of distortion in the image presented at the nominal eye point 608. Distortion introduced oblique incidence at surface 606 is compensated by oblique incidence at surface 614, and the element 604 also has diverging power in the horizontal direction, which reduces the system focal length in this section and stretches the image in this section. The design is optimised again for a field 40° high x 60° wide and for two eye pupils with a nominal separation of 70mm.

Optical design data for the system shown in figure 6 is presented in Table 6-1. The optical surfaces are listed in reverse optical order from the eye-point 608 back to the display 601, using the same numerals in the table as in figure 6. Separations, radii of curvature and shifts of optical surfaces are given in millimetres, and tilts of surfaces in degrees. Surfaces 605, 607, 614, 615 and 603, are toric, so that the table gives two radii of curvature for these surfaces. Surface 606 is spherical and very close to flat. The conventions of the table are the same as for Table 4-1.

Figure 7 shows an imaging system including a display source 701, which may be a 4 inches (100mm) LCD, a refracting block 702, a concave mirror 703 and refracting element 704. The block 702 is preferably made of plastic such as cyclic olefin copolymer (COC) and has three optical surfaces, 705, 706 and 707. The paths of light rays travelling from the source 701 to the user's eye at point 708, are indicated by the arrowed lines 711, 712, and 713. The light from the source 701 enters the block 702 through the top refracting surface 705. The light is then internally reflected at the surface 706 and leaves the block 702 at the surface 707. The light is reflected back into the block through surface 707 by the concave mirror 703. The light is refracted out of the block 702 at the surface 706. The light then passes through the refracting element 704, which has optical surfaces 709 and 710, and is then directed towards the eye point 708.

Part of the area of surface 706, indicated by the heavy line 714, is mirror-coated to ensure internal reflection of light from this part of the surface. However, the reflection of light from the other part of surface 706 is total internal reflection, so that it is not necessary for this other part to carry a mirror coating. The light finally emerges from the block 702 through that part of surface 706 that is not mirror coated. Surfaces 705, 707, 709 and 710, and the part of surface 706 that is not mirror-coated, may be anti-reflection coated to improve transmission of the optical system.

Table 7-1 Design data for system of figure 7

Surface	Radius-vertical (mm)	Radius - horizontal (mm)	Separation (mm)	Material	Tilt, degrees	Vertical shift (mm)
Eye point, 708						
			80	Air		
710	280	flat			---	---
			20	COC		
709	flat	flat			26.4	---
			0.125	Air		
706	flat	flat			26.6	---
			35	COC		
707	-212	-212			-5.1	---
			3.9	Air		
703	-321	-262			-11.9	---
			-3.9	Air		
707	-121	-212			-5.1	---
			-35	COC		
706	flat	flat			26.6	---
			7.5	COC		
705	139	flat			66.2	58.0
			0.5	Air		
701 (source)		flat			63.0	66.7

Light from each point on the source surface, is approximately collimated, collimation being produced in this case mainly by the effects of surfaces 703, 707 and 710. However, all surfaces can be curved to improve the correction of the design for optical aberrations.

The design in figure 7, like the design shown in figure 6, has an additional element, 704, in comparison with the design shown in figure 5. Again, a principal function of the additional element 704 is to improve control of distortion in the image presented at the nominal eye point 708. However, the element 704 also has fairly substantial power in surface 709. This reduces the necessary optical power of the mirror, which also tends to improve resolution and correction for binocular disparity. The design shown in figure 7 has relatively simple surface shapes, for ease of manufacture. It is optimised for a field 40° high x 52° wide and for two eye pupils with a nominal separation of 72mm.

Optical design data for the system shown in figure 7 is presented in Table 7-1. The optical surfaces are listed in reverse optical order from the eye-point 708 back to the display 701, using the same numerals in the table as in figure 7. Separations, radii of curvature and shifts of optical surfaces are given in millimetres, and tilts of surfaces in degrees. Surfaces 705 and 710 are cylindrical, surfaces 706 and 709 are flat, surface 707 is spherical, and the mirror surface 703 is toric. The conventions of the table are the same as for Table 4-1.

Figure 8 shows an imaging system including a display source 801, which may be a 4 inches (100mm) LCD, a refracting block 802, a concave mirror 803 and refracting element 804. The block 802 is preferably made of plastic such as polystyrene and has three optical surfaces, 805, 806 and 807. The paths of light rays travelling from the source 801 to the user's eye at point 808, are indicated by the arrowed lines 811, 812, and 813. The light from the source 801 enters the block 802 through the top refracting surface 805. The light is then internally reflected at the surface 806 and leaves the block 802 at the surface 807. The light is reflected back into the block through surface 807 by the concave mirror 803. The light is refracted out of the block 802 at the surface 806. The light then passes through the refracting element 804, which has optical surfaces 809 and 810, and is then directed towards the eye point 808.

Part of the area of surface 806, indicated by the heavy line 814, is mirror-coated to ensure internal reflection of light from this part of the surface. However, the reflection of light from the other part of surface 806 is total internal reflection, so that it is not necessary for this other part to carry a mirror coating. The light finally emerges from the block 802 through that part of surface 806 that is not mirror coated. Surfaces 805, 807, 809 and 810, and the part of surface 806 that is not mirror-coated, may be anti-reflection coated to improve transmission of the optical system.

Table 8-1 Design data for system of figure 8

Surface	Radius	Separation (mm)	Material	Tilt, degrees	Vertical shift (mm)
Eye point, 808					
		76	Air		
810	flat			17	---
		11.7	polystyrene		
809	-766.5			31.1	---
		4.6	Air		
806	flat			24	---
		28	polystyrene		
807	-233.4			-8.2	---
		2.7	Air		
803	-240.5			-12.2	---
		-2.7	Air		
807	-223.4			-8.2	---
		-28	polystyrene		
806	flat			24	---
		25	polystyrene		
805	flat			68	47.5
		-18.8	Air		
801 (source)	flat			58.5	65.2

Light from each point on the source surface, is approximately collimated, collimation being produced in this case mainly by the effects of surfaces 803 and 807. All optical surfaces in this design are made either flat or spherical to ease manufacture. Surfaces 805, 806 and 810 are flat and surfaces 803, 807 and 809 are spherical.

The design in figure 8, like the design shown in figure 6, has an additional element, 804, in comparison with the design shown in figure 5. Again, a principal function of the additional element 804 is to improve control of distortion in the image presented at the nominal eye point 808. The design is optimised for a field 40° high x 60° wide and for two eye pupils with a nominal separation of 72mm.

Optical design data for the system shown in figure 8 is presented in Table 8-1. The optical surfaces are listed in reverse optical order from the eye-point 808 back to the display 801, using the same numerals in the table as in figure 8. Separations, radii of curvature and shifts of optical surfaces are given in millimetres, and tilts of surfaces in degrees.

Figure 9 shows a perspective view of a firefighter's helmet with a display system in accordance with the invention mounted thereon. The firefighter's helmet 910 may be of any generally standard form comprising a fireproof, heat proof, impact absorbing shell. As is common, the helmet 910 (or its associated head harness) mounts a face mask 911 and breathing apparatus 912. Mounted to the side of the helmet (or its associated head harness) is an infrared camera 913 pointing forwards generally at the eye level of the firefighter. Mounted to the front of the helmet 910 is a display system 914 in accordance with any of the embodiments of the invention described. The display system 914 is mounted by means of an adjustable mount 916 and extends downwardly in front of the face of the firefighter. As is clear from Figure 9 the firefighter's eye 917 is positioned with respect to the display system at the point 406 in the arrangement of Figure 4, 507 in the arrangement of Figure 5, 608 in the arrangement of Figure 6, 708 in the arrangement of Figure 7. and 808 in the arrangement of Figure 8.

The image from the infrared camera 913 is displayed on an electronic video display which comprises the display source 501 in Figure 5 and corresponding parts of the remaining Figures. Thus the firefighter in looking into the display system 914 will see an image displayed on the display source 501 which will be an image as seen by the infrared camera. This enables the firefighter to see in dark or smoke filled environments and to readily distinguish hot spots or flames.

The adjustable mount 916 may be arranged so that the display system 914 may be readily pivoted away from the front of the firefighter's face so as to enable normal vision to be used.

In place of a firefighters helmet, the apparatus may be mounted on the helmet of an aircraft pilot, but in this case there may not be a camera mounted on the helmet, the video images being otherwise provided, for example from the weapons system.

Many other effective alternative configurations will occur to those skilled in the art and it should be understood that the system design is not limited to the described embodiments.

CLAIMS

1. An imaging system to accept an input image from an image source (501) and provide an output image, the system comprising:

a refracting block (502) having first (504), second (505) and third (506) optical surfaces; *characterised by*

a concave mirror surface (503) outside the third optical surface of said block;

an optical path extending from the image source (501) to an optical output (507) of the system;

the optical path including transmission through the first optical surface, internal reflection at the second optical surface, reflection at the concave mirror surface and transmission through the second optical surface.

2. An imaging system as claimed in any preceding claim wherein said internal reflection comprises total internal reflection and reflection from a coated mirror portion (512) of said second optical surface.

3. An imaging system as claimed in any preceding claim wherein said second optical surface is substantially flat.

4. An imaging system as claimed in any preceding claim further comprising a curved refracting element (604) in the optical path following transmission through the second optical surface.

5. An imaging system as claimed in claim 4 in which said refracting element is a curved wedge shaped element.

6. An imaging system as claimed in any preceding claim wherein the image source is an electro-optic image generator.

7. An imaging system as claimed in any preceding claim, including means (916) to mount said imaging system to a head or helmet and the image source comprises a video image display (501).

8. An imaging system as claimed in any preceding claim providing an image simultaneously to two eyes of a human user from a single image source.

9. A display system comprising:

a helmet (910) or head harness (915);

a camera (913) mounted to said helmet or head harness;

a display means (501) for receiving images from said camera;

an imaging system as claimed in any of claims 1 to 7 mounted to said helmet or head harness in such a position that the output image is passed to the eye of the wearer of the helmet or head harness.

10. A method of providing an enhanced field of view for a display system, the method comprising:

providing a refracting block (502), said block including a transmitting surface (506) and a reflecting surface (505);

providing an image source (501);

characterised by

providing a concave mirror (503) with a focal length comparable to an effective lateral dimension of the mirror;

providing the image source adjacent the mirror;

providing the refracting block in front of a reflecting surface of said mirror extending substantially across said lateral dimension of the mirror;

directing light from the image source into the block and, via the reflecting surface, onto the concave mirror; and

directing light from the concave mirror through the transmitting surface of said block to provide a user image, whereby said field of view of the user image is enhanced.

11. A method as claimed in claim 10 wherein said step of directing light via the reflecting surface includes totally internally reflecting light at the reflecting surface.

12. A method as claimed in claim 10 or 11 wherein said reflecting surface is partially coated to increase its reflectivity.

13. A method as claimed in any one of claims 10 to 12 whereby the field of view is enhanced by a factor approximately equal to the refractive index of the block.

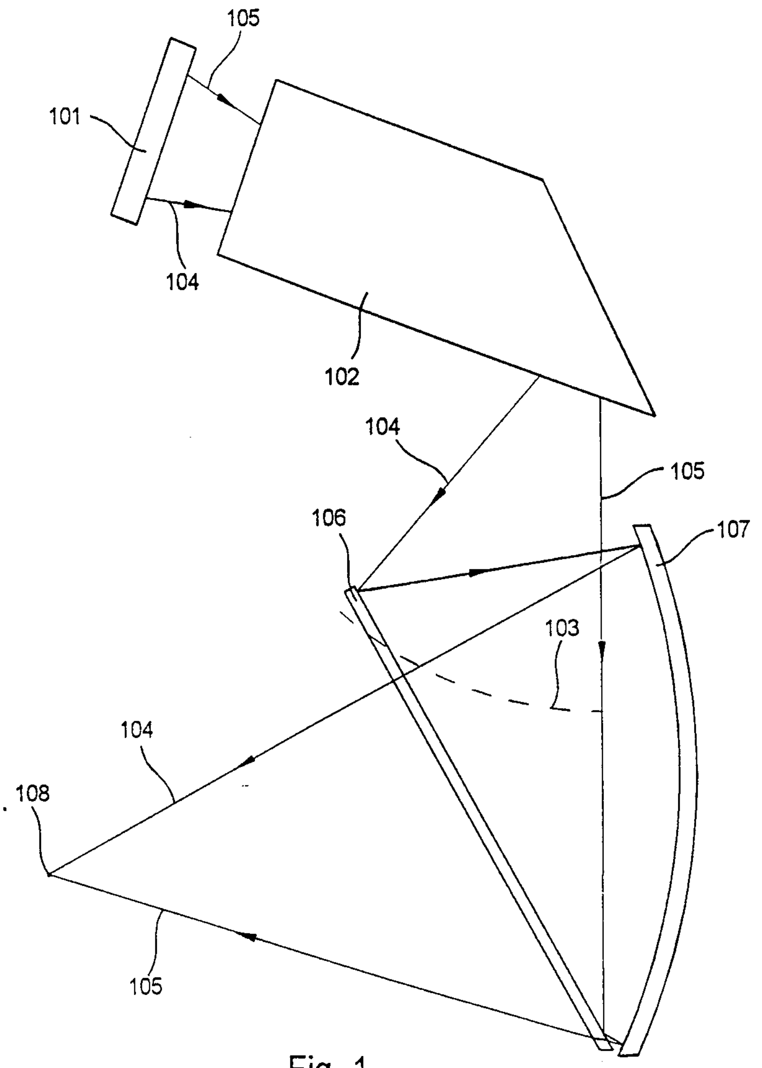

Fig. 1

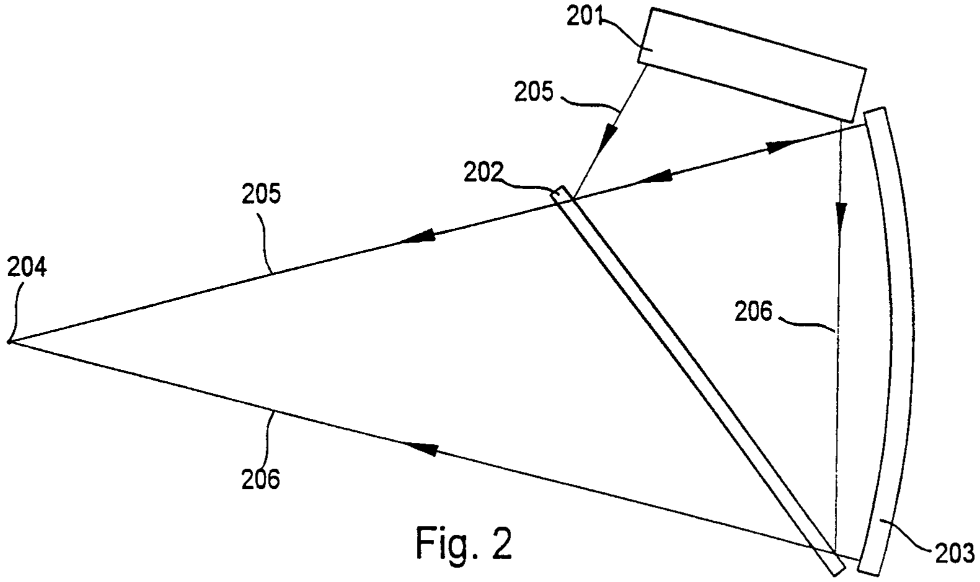

Fig. 2

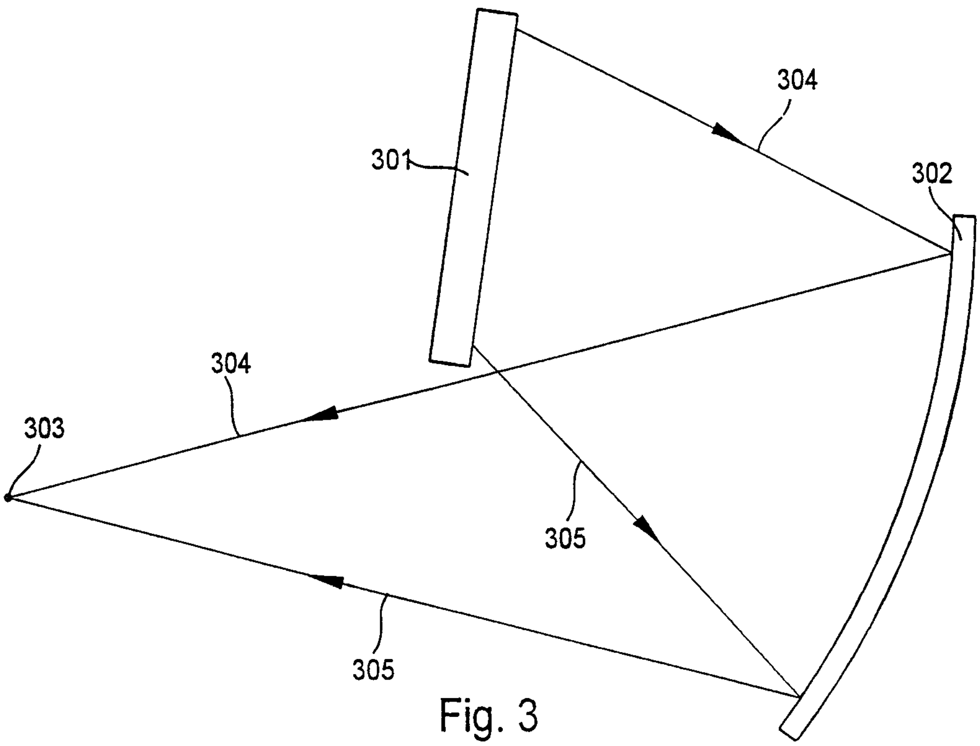

Fig. 3

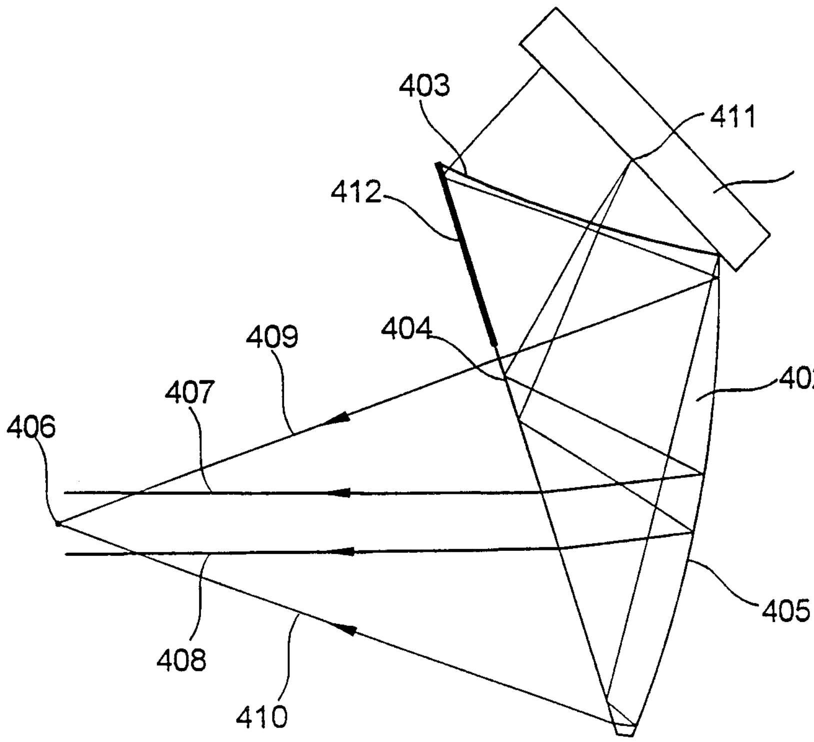

Fig. 4

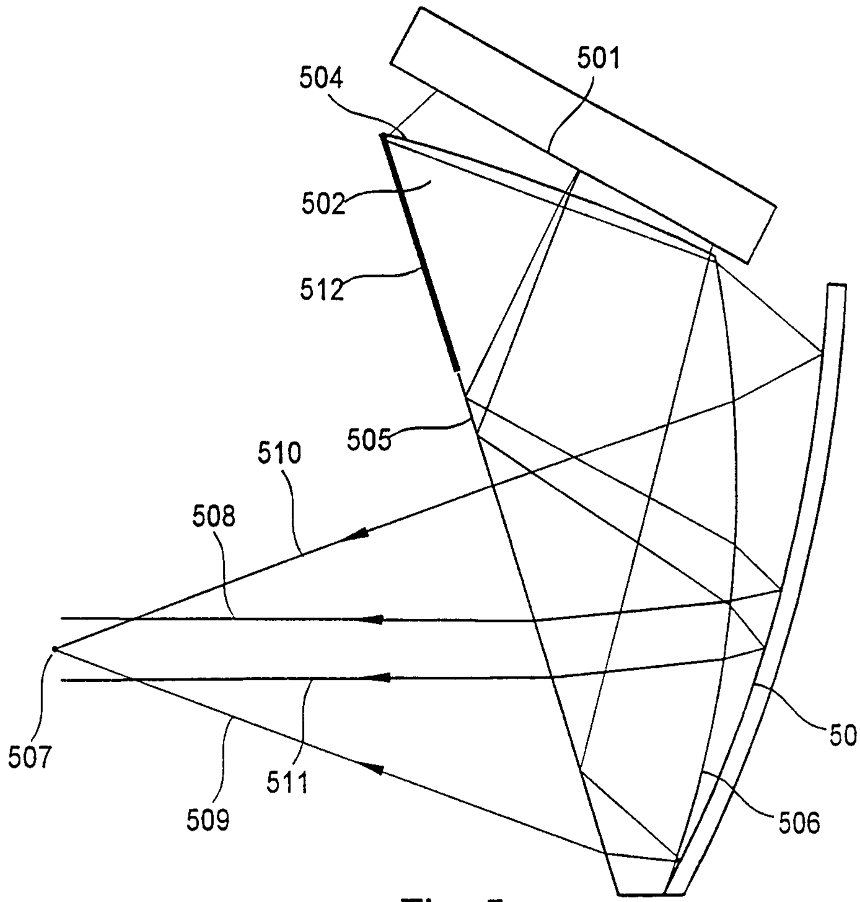

Fig. 5

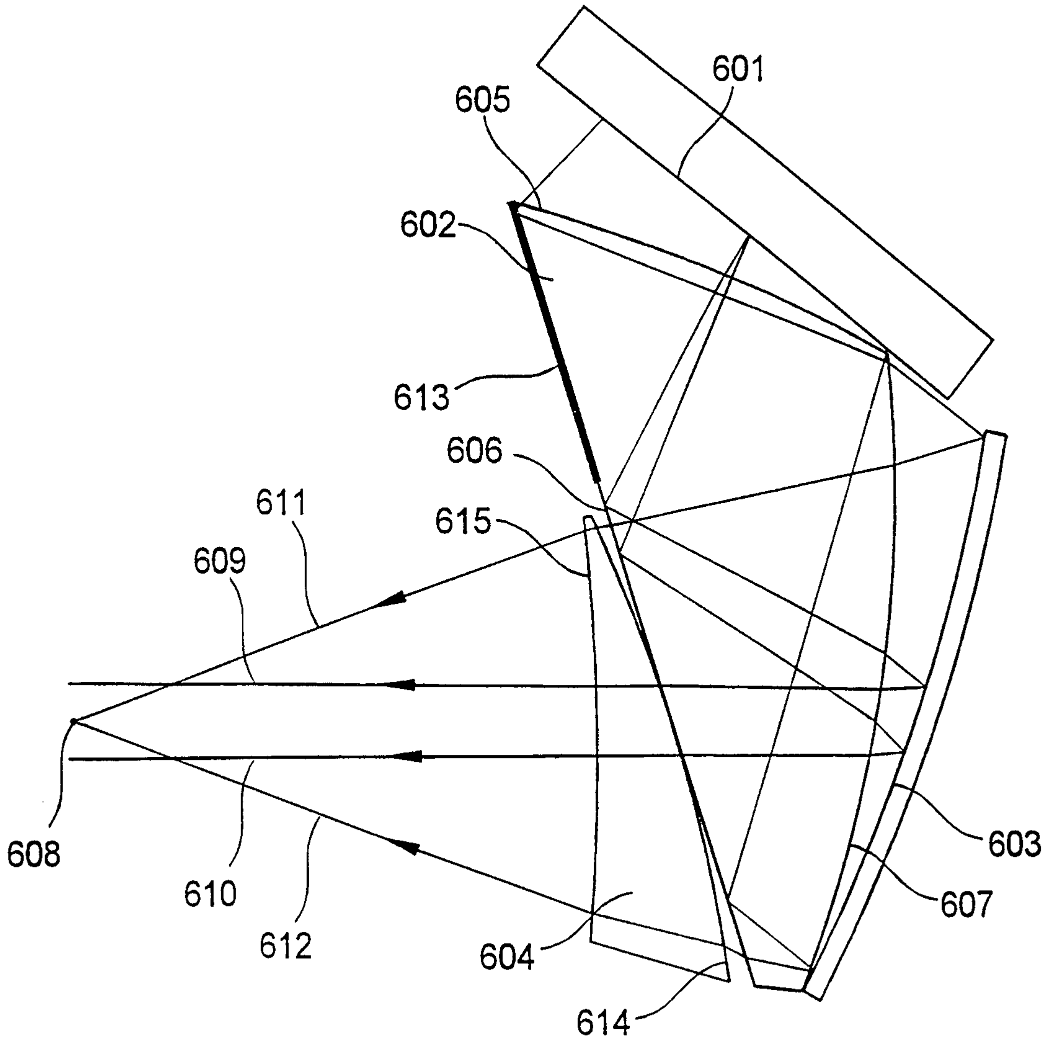

Fig. 6

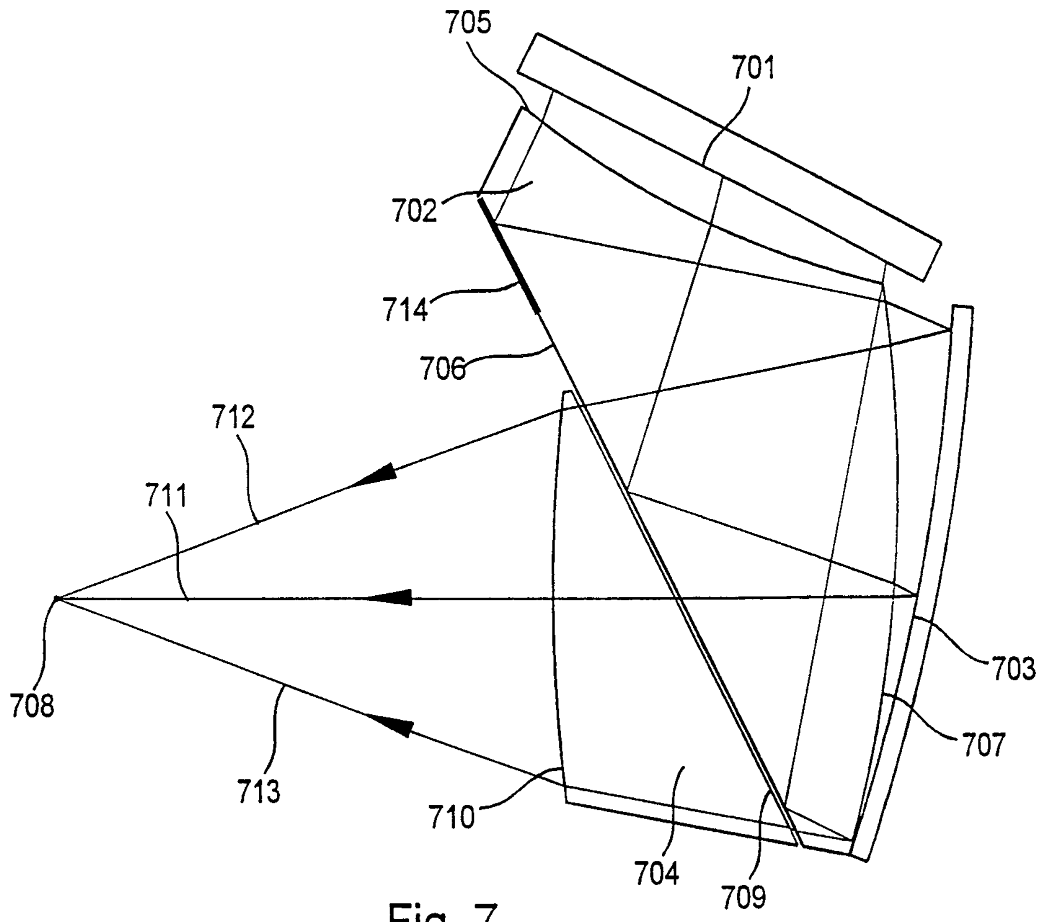

Fig. 7

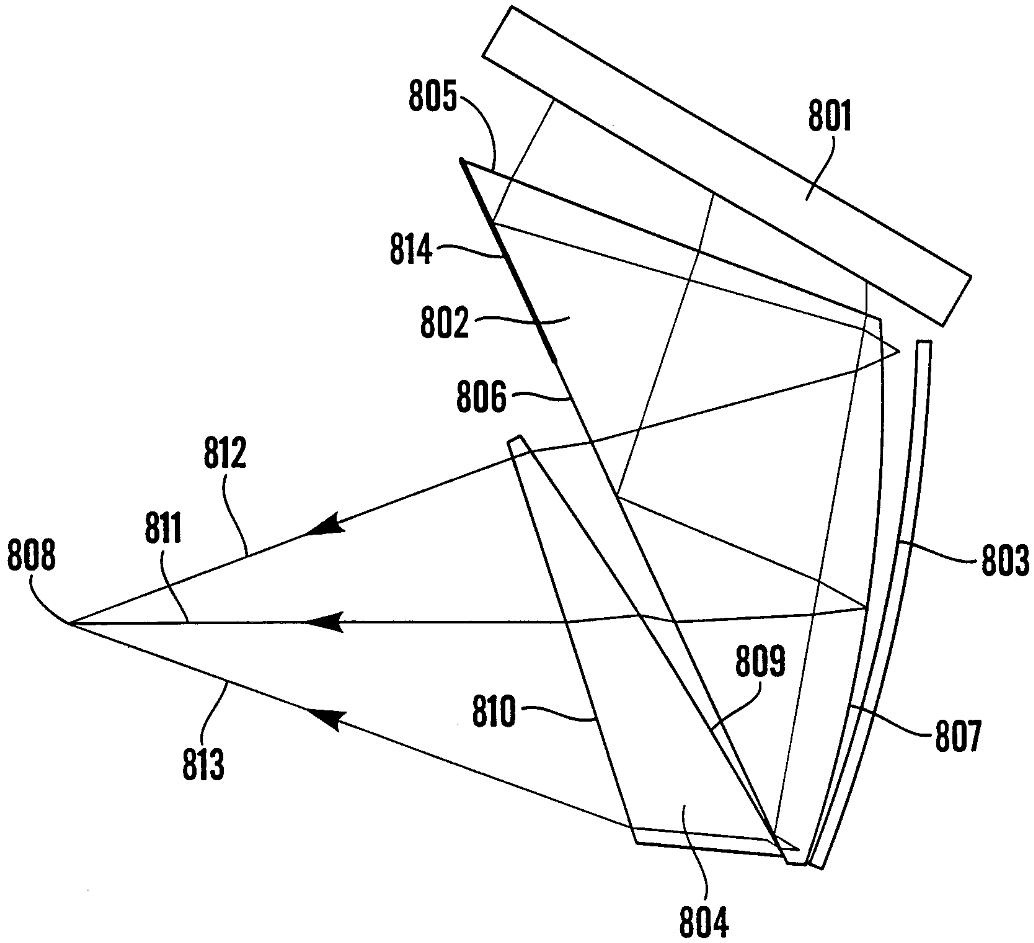

Fig.8

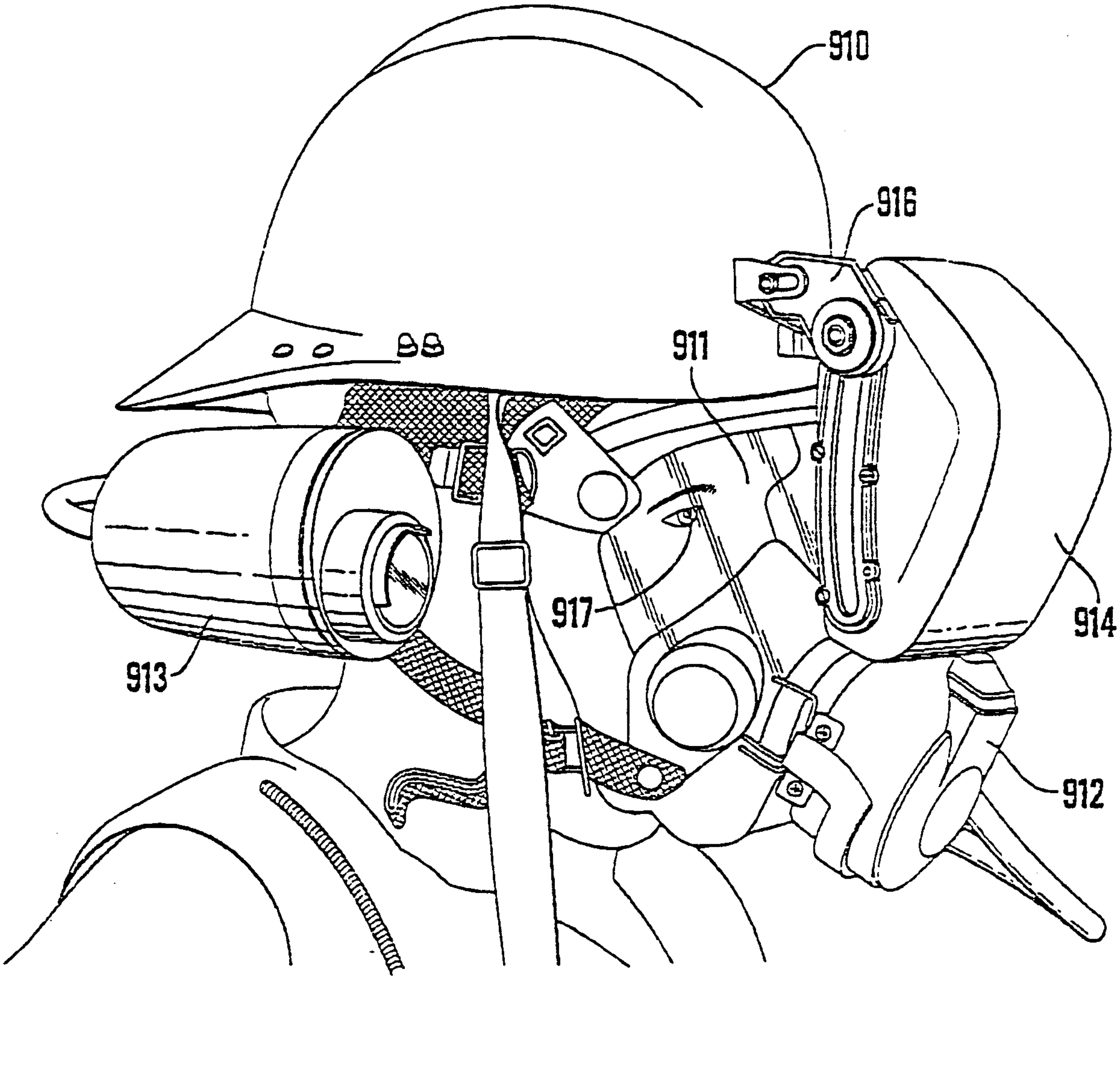

Fig.9

INTERNATIONAL SEARCH REPORT

International Application No
PCT/GB 99/02713

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 G02B17/08 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 7 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.
X	US 5 596 433 A (KONUMA) 21 January 1997 (1997-01-21) abstract column 7, line 16 - line 26; figure 2 ---	1,3,4,6, 7
X	JP 09 061747 A (TAKAHASHI) 7 March 1997 (1997-03-07)	1
A		2,10,11
P,X	& US 5 812 323 A (TAKAHASHI) 22 September 1998 (1998-09-22) abstract column 10, line 10 - line 15	1
P,A	column 11, line 38 - line 47; figure 4 ---	2,10,11
X	EP 0 077 193 A (MARCONI) 20 April 1983 (1983-04-20) page 7, column 3 -column 11; figure 8	10-12
A	---	2
	-/--	

[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

° Special categories of cited documents :

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"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
30 November 1999	07/12/1999

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Soulaire, D

3

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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 5 745 295 A (TAKAHASHI) 28 April 1998 (1998-04-28) cited in the application abstract column 12, line 3 - line 22; figure 3 ---	1,4,5
A	US 5 701 202 A (TAKAHASHI) 23 December 1997 (1997-12-23) cited in the application column 1, line 5 - line 7 column 15, line 36 - line 43 column 16, line 62 -column 17, line 6; figure 8 ---	1,4,5
A	GB 2 238 627 A (YAZAKI) 5 June 1991 (1991-06-05) page 50, last paragraph -page 52, paragraph 2; figures 33,34 ---	8
A	EP 0 691 559 A (GEC-MARCONI) 10 January 1996 (1996-01-10) abstract column 2, line 56 -column 3, line 15; figures -----	9

INTERNATIONAL SEARCH REPORT

Information on patent family members

International Application No
PCT/GB 99/02713

Patent document cited in search report		Publication date	Patent family member(s)			Publication date
US 5596433	A	21-01-1997	JP	6308424	A	04-11-1994
JP 9061747	A	07-03-1997	US	5940218	A	17-08-1999
			US	5812323	A	22-09-1998
EP 77193	A	20-04-1983	BR	8205968	A	13-09-1983
			GB	2108702	A,B	18-05-1983
			JP	1844363	C	25-05-1994
			JP	5019130	B	15-03-1993
			JP	58078116	A	11-05-1983
			US	4775217	A	04-10-1988
US 5745295	A	28-04-1998	JP	9146037	A	06-06-1997
US 5701202	A	23-12-1997	JP	8313829	A	29-11-1996
			US	5875056	A	23-02-1999
GB 2238627	A	05-06-1991	JP	3251816	A	11-11-1991
			JP	2803757	B	24-09-1998
			JP	3225317	A	04-10-1991
			DE	4037879	A	06-06-1991
			US	5266930	A	30-11-1991
EP 691559	A	10-01-1996	GB	2291304	A	17-01-1996
			JP	8054282	A	27-02-1996