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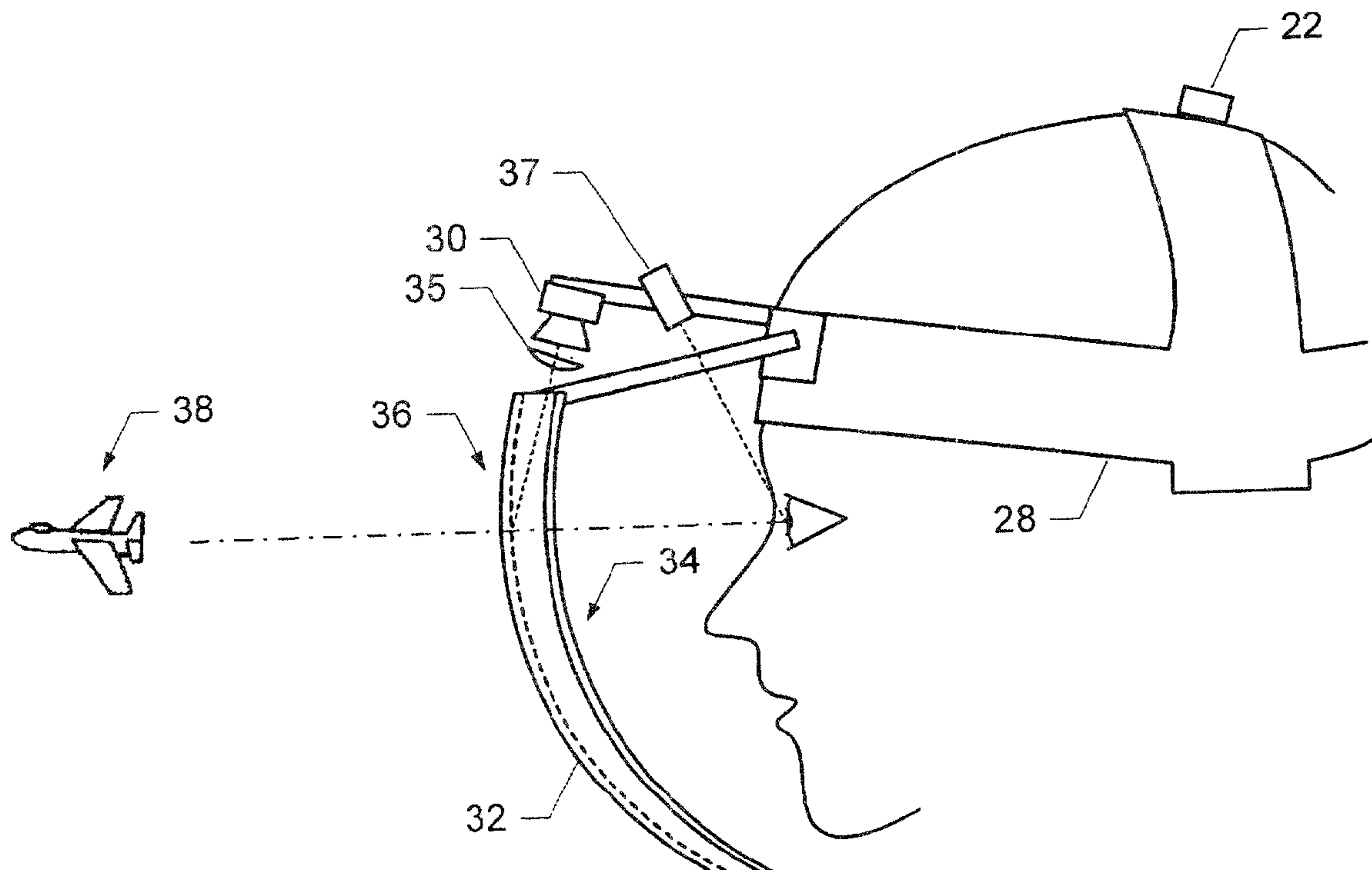
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(57) Abrégé/Abstract:

A system for tracking a gaze of an operator includes a head-mounted eye tracking assembly, a head-mounted head tracking assembly and a processing element. The head-mounted eye tracking assembly comprises a visor having an arcuate shape

(57) **Abrégé(suite)/Abstract(continued):**

including a concave surface and an opposed convex surface. The visor is capable of being disposed such that at least a portion of the visor is located outside a field of view of the operator. The head-mounted head tracking sensor is capable of repeatedly determining a position of the head to thereby track movement of the head. In this regard, each position of the head is associated with a position of the at least one eye. Thus, the processing element can repeatedly determine the gaze of the operator, based upon each position of the head and the associated position of the eyes, thereby tracking the gaze of the operator.

GAZE TRACKING SYSTEM, EYE-TRACKING ASSEMBLY AND AN ASSOCIATED METHOD OF CALIBRATION

ABSTRACT OF THE DISCLOSURE

A system for tracking a gaze of an operator includes a head-mounted eye
5 tracking assembly, a head-mounted head tracking assembly and a processing element.
The head-mounted eye tracking assembly comprises a visor having an arcuate shape
including a concave surface and an opposed convex surface. The visor is capable of
being disposed such that at least a portion of the visor is located outside a field of
view of the operator. The head-mounted head tracking sensor is capable of repeatedly
10 determining a position of the head to thereby track movement of the head. In this
regard, each position of the head is associated with a position of the at least one eye.
Thus, the processing element can repeatedly determine the gaze of the operator, based
upon each position of the head and the associated position of the eyes, thereby
tracking the gaze of the operator.

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GAZE TRACKING SYSTEM, EYE-TRACKING ASSEMBLY AND AN ASSOCIATED METHOD OF CALIBRATION

FIELD OF THE INVENTION

5 The present invention relates generally to head/eye tracking systems for visual display systems and, more particularly, to head/eye tracking systems including an eye tracking device having a curved visor.

BACKGROUND OF THE INVENTION

Visual display systems, such as flight simulation systems, are commonly employed to train military and commercial pilots. Conventional visual display
10 systems include one or more screens onto which a video image is projected by one or more projectors containing image sources, such as cathode ray tubes (CRTs). The operator of the visual display system is also generally provided with a control panel and, in some instances, a joystick for providing input to the visual display system in response to the displayed video image. In this regard, the control panel and joystick
15 are often designed to duplicate the controls and displays found in an aircraft. Thus, the operator can simulate the flight of an aircraft, for example, and can respond to the environment as depicted by the visual display.

In order to provide a relatively large display for the operator, the video image produced by the projector of a conventional flight simulation system is generally
20 expanded and displayed upon a screen having a much larger surface area than the surface of the image source. For example, each optical line pair of a conventional projector generally defines a projection angle of 7 to 12 arcminutes. Thus, while a relatively large image is displayed for the operator, the resolution of the image is somewhat diminished by the expansion of the video image.

25 To improve the effective resolution of the projected video image, systems and methods have been developed to inset a high resolution video image into the displayed video image or background image. The high resolution inset image is generally relatively small and is, for example, positioned at an area of interest, such as the portion of the screen that the operator is currently viewing. The high resolution
30 inset image generally has a small relative size, taking advantage of the human visual system's limited ability to see clear images outside a small area surrounding the line

of sight. The small region surrounding the line of sight corresponds to the foveal region of the human eye and, therefore, the corresponding ability to see high detail in the region surrounding the line of sight is typically referred to as foveal vision. This high resolution inset image, which is positioned to generally follow the operator's line of sight, is typically referred to as the Area of Interest (AOI) display. The line of sight including the foveal vision of the operator is generally defined by (1) the direction the operator's head faces, and (2) the direction the operator's eyes face relative to the position of the operator's head.

An area of interest 8 is typically determined by a head/eye tracking device, as shown in FIG. 1. As shown, to track the operator's head position, the head/eye tracking device 10 includes a head tracker sensor 12 mounted above the operator's head by means of a headband 14, helmet, or other securing device worn on the operator's head so that the position of the head/eye tracking device is held fixed in position and orientation relative to the operator's head. To track the position of the operator's eyes, the head/eye tracking device includes a video camera 16 mounted above and forward of the operator's head by means of the headband or other head-mounted securing device. The image capture device tracks the position of the operator's eyes by imaging the pupils of the operator's eyes through a partially reflective/partially transmissive flat mirror 18, which is mounted in front of the operator's eyes. By imaging the operator's pupils through the mirror, the image capture device can be mounted in a position out of the operator's visual field of view. In operation, before the head/eye tracking device 10 can track position of the operator's head and eyes, the head/eye tracking device must be calibrated with the screen upon which the video image produced by the projector is displayed.

According to one conventional method of calibrating the head/eye tracking device, a plurality of calibration points are displayed upon the screen, such as nine calibration points displayed in a 3x3 matrix. Then, to calibrate the head tracker sensor 12 of the head/eye tracking device, the operator moves his head and, thus, the head tracker sensor such that one of the calibration points is in line with a fixed reference point attached to the head/eye tracker. A data point is then recorded based upon the position of the head tracker sensor. The operator then repeats the process for each of the calibration points displayed upon the screen, with a data point recorded at each calibration point. Once a data point has been recorded for all calibration points, a head tracking calibration function is calculated based upon the recorded data points.

Either before or after calibrating the head tracker sensor, the image capture device of the head/eye tracker must be calibrated with the screen so that the head/eye tracking device can accurately track the position of the operator's eyes relative to the head tracker sensor. To calibrate the image capture device, the calibration points are again displayed upon the screen. The operator then orients his head and, thus the head tracker sensor, in a fixed position, preferably such that the operator's line of sight intersects a center point of the screen. Holding his head in the fixed position, the operator moves his eyes such that the operator's line of sight intersects one of the calibration points. A data point is then recorded for the calibration point based upon an image of the operator's pupils taken by the image capture device. In this regard, the data point can include information such as pupil position in both the X and Y directions, as well as corneal reflection in both the X and Y directions. Also as before, the operator repeats the process of moving his eyes to each calibration point and recording a data point for each calibration point, all while holding his head in the fixed position. And after the data points have been recorded for all of the calibration points, an eye tracking calibration function is calculated based upon the recorded data points, e.g., (eye pitch, eye yaw) = f(input data from tracker).

After calculating the calibration functions, the head/eye tracking device tracks the position of the operator's head based upon the position of the operator's head as determined by the head tracker sensor, and based upon the head tracking calibration function. Similarly, the head/eye tracking device tracks the position of the operator's eyes as determined by the image capture device, and based upon the eye tracking calibration function. And based upon the position of the operator's head and pupils at any given time, the area of interest is selected relative to the screen and thereafter displayed, such as in line with the operator's line of sight. The high resolution inset image can then be projected within the area of interest to thereby be within the operator's foveal vision.

Whereas conventional head/eye tracking devices are adequate in tracking the head and eye position of the operator, such conventional tracking devices have drawbacks. The partially reflective/partially transmissive flat mirror 18, which is mounted in front of the operator's eyes, is visually distracting for the operator. In this regard, the mirror is an unnatural obstruction in the operator's visual field of view, limiting the operator's feeling of visual immersion in a virtual reality application, such as that found in flight simulation systems.

In addition to the structural drawback of the partially reflective/partially transmissive flat mirror **18**, the method by which conventional head/eye tracking devices are calibrated also has drawbacks. As stated before, either the operator's eyes or head must remain in a fixed position for a period of time during various stages of calibrating the head/eye tracking device. In this regard, the calibration method is prone to errors caused by inadvertent movement of either the operator's eyes or head during a time in which the eyes or head must remain in a fixed position for complete accuracy. Due to the time period the operator is required to keep either his eyes or head in the fixed position, the operator can have a tendency to fatigue, which can cause the operator's eyes or head to inadvertently move.

SUMMARY OF THE INVENTION

In accordance with one aspect of the invention there is provided a head-mounted eye tracking assembly for tracking movement of at least one eye of an operator. The eye tracking assembly includes a visor having an arcuate shape including a concave surface and an opposed convex surface, wherein the visor is capable of being disposed such that the at least one eye is located proximate the concave surface, wherein the visor is at least partially reflective such that the visor is capable of reflecting an image of the at least one eye, and wherein the visor is capable of being disposed such that at least a portion of the visor is located outside a field of view of the operator. The eye tracking assembly further includes an image capture device disposed proximate the concave surface of the visor, wherein the image capture device is capable of tracking movement of the at least one eye based upon the image of the at least one eye reflected by the visor.

The concave surface of the visor may include a reflective coating.

The head-mounted eye tracking assembly may further include an illuminator capable of illuminating the at least one eye.

The illuminator may be capable of illuminating the at least one eye with infrared light.

The head-mounted eye tracking assembly may further include a lens disposed in an optical path of the image capture device, wherein an effective focus of the image capture device is based upon an optical power of the visor and an optical power of the lens.

The image capture device may be located outside the field of view of the operator.

In accordance with another aspect of the invention, there is provided a system for tracking a gaze of an operator. The gaze tracking system includes a head-mounted eye tracking assembly. The head-mounted eye tracking assembly further includes a visor having an arcuate shape including a concave surface and an opposed convex surface, wherein the visor is capable of being disposed such that at least one eye is located proximate the concave side, wherein the visor is at least partially reflective such that the visor is capable of reflecting an image of the at least one eye, wherein the visor is capable of being disposed such that at least a portion of the visor is located outside a field of view of the operator, and wherein the head-mounted eye tracking assembly is capable of repeatedly determining a position of the at least one eye based upon the image of the at least one eye reflected by the visor to thereby track movement of the at least one eye. The head-mounted eye tracking assembly further includes a head-mounted head tracking sensor capable of repeatedly determining a position of the head to thereby track movement of the head, wherein each position of the head is associated with a position of the at least one eye. The head-mounted eye tracking assembly further includes a processing element capable of repeatedly determining the gaze of the operator to thereby track the gaze of the operator, wherein the processing element repeatedly determines the gaze of the operator based upon each position of the head and the associated position of the at least one eye.

The concave surface of the visor of the head-mounted eye tracking assembly may include a reflective coating.

The head-mounted eye tracking assembly may further include an illuminator capable of illuminating the at least one eye.

The illuminator may be capable of illuminating the at least one eye with infrared light.

The head-mounted eye tracking assembly may further include an image capture device disposed proximate the concave surface of the visor, and wherein the image capture device is capable of tracking movement of the at least one eye based upon the image of the at least one eye reflected by the visor.

The head-mounted eye tracking assembly may further include a lens disposed in an optical path of the image capture device, wherein an effective focus of the image capture device is based upon an optical power of the visor and an optical power of the lens.

5 The image capture device may be located outside the field of view of the operator.

10 In accordance with another aspect of the invention, there is provided a visual display system. The visual display system includes a background image projector having a predetermined field of view, the background image projector generating a background image having a predetermined size and resolution that at least partially fills the field of view. The visual display system further includes at least one inset image projector for generating an area of interest (AOI) image having a smaller size and a higher resolution than the background image, the inset image projector having a predetermined field of view that is capable of being movably disposed at least partially within the field of view of the background image projector. The visual display system further includes a gaze tracking system capable of directing the movement of the field of view of the inset image projector based upon the direction in which an operator is looking. The gaze tracking system includes a head-mounted eye tracking assembly. The head-mounted eye tracking assembly includes a visor having an arcuate shape including a concave surface and an opposed convex surface, wherein the visor is capable of being disposed such that at least one eye is located proximate the concave surface, wherein the visor is at least partially reflective such that the visor is capable of reflecting an image of the at least one eye, and wherein the visor is capable of being disposed such that at least a portion of the visor is located outside a field of view of an operator. The head-mounted eye tracking assembly further includes an image capture device disposed proximate the concave surface of the visor, wherein the image capture device is capable of tracking movement of the at least one eye based upon the image of the at least one eye reflected by the visor.

25 The gaze tracking system may further include a head-mounted head tracking sensor capable of repeatedly determining a position of the head to thereby track movement of the head, wherein each position of the head is associated with a position of the at least one eye. The gaze tracking system may further include a processing element capable of repeatedly determining a gaze of the operator to thereby track the gaze of the operator, wherein the processing element repeatedly determines the gaze

of the operator based upon each position of the head and the associated position of the at least one eye.

The concave surface of the visor of the head-mounted eye tracking assembly may include a reflective coating.

5 The head-mounted eye tracking assembly may further include an illuminator capable of illuminating the at least one eye.

10 The head-mounted eye tracking assembly may further include a lens disposed in an optical path of the image capture device, wherein an effective focus of the image capture device is based upon an optical power of the visor and an optical power of the lens.

15 In accordance with another aspect of the invention, there is provided a head-mounted eye tracking assembly for tracking movement of at least one eye of an operator. The eye tracking assembly includes a visor having an arcuate shape including a concave surface and an opposed convex surface, wherein the visor is capable of being disposed such that the at least one eye is located proximate the concave surface, wherein the visor is at least partially reflective such that the visor is capable of reflecting an image of the at least one eye, and wherein the visor is capable of being disposed such that at least a portion of the visor is located outside a field of view of the operator. The eye tracking assembly further includes an image capture device disposed proximate the concave surface of the visor, wherein the image capture device is capable of tracking movement of the at least one eye based upon the image of the at least one eye reflected by the visor. The eye tracking assembly further includes a lens disposed in an optical path of the image capture device wherein an effective focus of the image capture device is based upon an optical power of the visor and an optical power of the lens.

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The concave surface of the visor may include a reflective coating.

The head-mounted eye tracking assembly may further include an illuminator capable of illuminating the at least one eye.

30 The illuminator may be capable of illuminating the at least one eye with infrared light.

The image capture device may be located outside the field of view of the operator.

The visor may be capable of reflecting an image of a pupil of at least one eye, and wherein the image capture device is capable of tracking movement of the at least one eye based upon the image of the pupil of the at least one eye.

5 In accordance with another aspect of the invention, there is provided a system for tracking a gaze of an operator. The gaze tracking system includes a head-mounted eye tracking assembly. The head-mounted tracking assembly includes a visor having an arcuate shape including a concave surface and opposed an convex surface, wherein the visor is capable of being disposed such that the at least one eye is located proximate the concave side, wherein the visor is at least partially reflective such that
10 the visor is capable of reflecting an image of the at least one eye, wherein the visor is capable of being disposed such that at least a portion of the visor is located outside a field of view of the operator, and wherein the head-mounted eye tracking assembly is capable of repeatedly determining a position of the at least one eye based upon the image of the at least one eye reflected by the visor to thereby track movement of the
15 at least one eye. The head-mounted tracking assembly further includes an image capture device disposed proximate the concave surface of the visor, wherein the image capture device is capable of tracking movement of the at least one eye based upon the image of the at least one eye reflected by the visor. The head-mounted tracking assembly further includes a lens disposed in an optical path of the image
20 capture device, wherein an effective focus of the image capture device is based upon an optical power of the visor and an optical power of the lens. The gaze tracking system further includes a head-mounted head tracking sensor capable of repeatedly determining a position of the head to thereby track movement of the head, wherein each position of the head associated with a position of the at least one eye. The gaze
25 tracking system further includes a processing element capable of repeatedly determining the gaze of the operator to thereby track the gaze of the operator, wherein the processing element repeatedly determines the gaze of the operator based upon each position of the head and the associated position of the at least one eye. The concave surface of the visor of the head-mounted eye tracking assembly may
30 include a reflective coating.

The head-mounted eye tracking assembly may further include an illuminator capable of illuminating the at least one eye.

The illuminator may be capable of illuminating the at least one eye with infrared light.

The image capture device may be located outside the field of view of the operator.

5 The visor may be capable of reflecting an image of a pupil of at least one eye, and wherein the head-mounted eye tracking assembly is capable of repeatedly determining a position of the at least one eye based upon the image of the pupil of the at least one eye.

10 In accordance with another aspect of the invention, there is provided a visual display system. The visual display system includes a background image projector having a predetermined field of view, the background image projector generating a background image having a predetermined size and resolution that at least partially fills the field of view. The visual display system further includes at least one inset image projector for generating an area of interest (AOI) image having a smaller size and a higher resolution than the background image, the inset image projector having a predetermined field of view that is capable of being movably disposed at least
15 partially within the field of view of the background image projector. The visual display system further includes a gaze tracking system capable of directing the movement of the field of view of the inset image projector based upon the direction in which an operator is looking. The gaze tracking system includes a head-mounted eye tracking assembly. The head-mounted eye tracking assembly includes a visor having
20 an arcuate shape including a concave surface and an opposed convex surface, wherein the visor is capable of being disposed such that the at least one eye is located proximate the concave surface, wherein the visor is at least partially reflective such that the visor is capable of reflecting an image of the at least one eye, and wherein the visor is capable of being disposed such that at least a portion of the visor is located
25 outside a field of view of the operator. The head-mounted eye tracking assembly further includes an image capture device disposed proximate the concave surface of the visor, wherein the image capture device is capable of tracking movement of the at least one eye based upon the image of the at least one eye reflected by the visor. The head-mounted eye tracking assembly further includes a lens disposed in an optical
30 path of the image capture device, wherein an effective focus of the image capture device is based upon an optical power of the visor and an optical power of the lens.

The gaze tracking system may further include a head-mounted head tracking sensor capable of repeatedly determining a position of the head to thereby track movement of the head, wherein each position of the head is associated with a position

of the at least one eye. The gaze tracking system may further include a processing element capable of repeatedly determining the gaze of the operator to thereby track the gaze of the operator, wherein the processing element repeatedly determines the gaze of the operator based upon each position of the head and the associated position
5 of the at least one eye.

The concave surface of the visor of the head-mounted eye tracking assembly may include a reflective coating.

The head-mounted eye tracking assembly may further include an illuminator capable of illuminating the at least one eye.

10 The head-mounted eye tracking assembly may further include a lens disposed in an optical path of the image capture device, wherein an effective focus of the image capture device is based upon an optical power of the visor and an optical power of the lens.

The visor may be capable of reflecting an image of a pupil of at least one eye,
15 and wherein the image capture device is capable of tracking movement of the at least one eye based upon the image of the pupil of the at least one eye.

The inset image projector may have a predetermined field of view that is capable of being movably disposed based upon electronic raster deflection.

BRIEF DESCRIPTION OF THE DRAWINGS

20 Having thus described the invention in general terms, reference will now be made to the accompanying drawings, which are not necessarily drawn to scale, and wherein:

FIG. 1 is a schematic illustration of portions of a conventional gaze tracking system;

25 FIG. 2 is a schematic illustration of portions of a gaze tracking system according to one embodiment of the present invention;

FIG. 3 is a block diagram of a gaze tracking system according to one embodiment of the present invention;

30 FIGS. 4A and 4B are schematic illustrations illustrating various movements in a method for calibrating the gaze tracking system according to one embodiment of the present invention;

FIG. 5 is a flow chart illustrating various steps in a method of calibrating a gaze tracking system according to one embodiment of the present invention; and

FIG. 6 is a perspective view illustrating a visual display system incorporating the gaze tracking system of one embodiment of the present invention.

DETAILED DESCRIPTION OF THE INVENTION

5 The present invention now will be described more fully hereinafter with reference to the accompanying drawings, in which preferred embodiments of the invention are shown. This invention may, however, be embodied in many different forms and should not be construed as limited to the embodiments set forth herein; rather, these embodiments are provided so that this disclosure will be thorough and
10 complete, and will fully convey the scope of the invention to those skilled in the art. Like numbers refer to like elements throughout.

Referring to FIGS. 2 and 3, a gaze tracking system **20** according to one embodiment of the present invention is shown. The system includes a head-mounted head tracking sensor **22**, a head-mounted eye tracking assembly **24**, and a processing
15 element **26**. The head tracking sensor and eye tracking assembly are mounted to an operator's head by means of a headband **28**, helmet or other head-mounted securing device. The head tracking sensor is mounted to the operator's head out of the field of vision of the operator so as to not impede the operator's vision. The head tracking sensor is capable of repeatedly determining a position of the operator's head to
20 thereby track the movement of the head. In this regard, the head tracking sensor can comprise any of a number of known sensors capable of determining the position of the operator's head. For example, the head tracker sensor can comprise an InsideTrak™ model head tracking sensor or a FasTrak™ model head tracking sensor, both manufactured by Polhemus Incorporated of Colchester, VT. Alternatively, the
25 head tracker sensor can comprise any of a number of other head tracking sensors that operate based on magnetic, acoustic, optical or other technologies, as such are known to those skilled in the art.

The eye tracking assembly comprises an image capture device **30** and a visor **32**. The visor is secured to the headband **28** such that, when the headband is mounted
30 to the operator's head, the visor is disposed in front of the operator's head. The visor is preferably at least partially reflective for light of a predetermined wavelength or range of wavelengths. For example, the visor may be made from a partially reflective material, such as Lexan® brand polycarbonate (manufactured by the General Electric Company of Pittsfield, MA) coated with a reflective film, so that the operator's field

of view can extend through the visor while an image of the operator's eyes, or more particularly the operator's pupils, reflects off of the visor into the optical path of the image capture device. Advantageously, the visor is designed to provide an environment for the operator that is typically found in many applications employing the system, such as flight simulation applications. In this regard, the visor is designed to not present any visually obstructive edges with the operator's field of view. Thus, the visor has an arcuate or curved shape including a concave surface **34** and an opposed convex surface **36**, one of which may support an at least partially reflective coating. The visor is secured to the headband such that, when the headband is

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mounted to the operator's head, the concave surface is disposed proximate the operator's eyes. Further, the visor is secured to the headband such that, when the headband is mounted to the operator's head, at least a portion of the visor is located outside the operator's field of view.

5 Like the head tracking sensor 22, the image capture device 30 is mounted outside the field of view of the operator so as to not impede the operator's vision. In this regard, the image capture device is preferably mounted on a front portion of the headband 28 such that the image capture device is located at a position peripheral to the operator's head out of the operator's field of view. The image capture device is
10 capable of repeatedly determining a position of the operator's eyes by imaging the pupil of one or both of the operator's eyes. Because the image capture device is mounted on the headband outside the field of view of the operator, the image capture device images the operator's pupils by imaging a reflection of the pupils from the visor of the eye tracking assembly. Thus, the image capture device can comprise any
15 of a number of devices capable of repeatedly determining the position of the operator's eyes to thereby track the movement of the operator's eyes. According to one embodiment, for example, the image capture device comprises a camera, such as is included within ETL-500 model eye tracking system manufactured by ISCAN, Inc. of Burlington, MA.

20 Advantageously, the image capture device 30 can comprise a camera, such as is used in a conventional head/eye tracking device including a partially reflective/partially transmissive flat mirror 18, as shown in FIG. 1. But it will be appreciated that the visor 32 of the present invention will typically have a different optical power than the flat mirror of the conventional head/eye tracking device. In
25 this regard, lenses have a characteristic power that is typically measured in diopters and equals the inverse of the focal length of the lens in meters, as such is known to those skilled in the art. It will also be appreciated that, in using a camera such as is used in a conventional head/eye tracking device, the effective focus of the camera will differ from the desired effective focus due to the difference in optical power between
30 the visor and the conventional flat mirror. Thus, in embodiments where the image capture device comprises a camera such as is used in a conventional head/eye tracking device, the system preferably compensates for the change effective focus due to the difference in optical power so as to bring the effective focus to a desired value, or the

value of the effective focus of the camera as used in the conventional head/eye tracking device.

The system **20** can compensate for the optical power of the visor **32** in any of a number of different manners. For example, the aperture of the camera lens can be reduced to thereby increase the depth-of-field of the camera. And by increasing the depth-of-field of the camera, the system can compensate for the change in effective focus of the camera. Additionally or alternatively, the system can include a lens **35** disposed in the optical path of the camera to compensate for the optical power of the visor. In this regard, if the aperture of the camera lens is not reduced, the lens can be selected such that the optical power of the lens plus the optical power of the visor equals the optical power of a flat mirror as would be included in a conventional head/eye tracking device including the camera.

As previously stated, the image capture device **30** images the operator's pupils by receiving light reflected off of the pupils and thereafter off of the visor **32** into the optical path of the image capture device. To facilitate tracking the eyes, the system **20** can include an illuminator **37** capable of illuminating the eyes such that more light reflects off of the eyes and, thus, the visor. However, to avoid visual distractions, the illuminator is preferably an infrared illuminator, such as an infrared light emitting diode, capable of illuminating infrared light to the eyes. The infrared light, thus, reflects off of the front and rear surfaces of the corneas and the lenses of the eyes, and thereafter reflects off of the visor into the optical path of the camera. It will be appreciated that such images are commonly referred to as Purkinje images by those skilled in the art. It will also be appreciated that as the light in this embodiment comprises infrared light, the image capture device of this embodiment is preferably infrared sensitive, such as an infrared sensitive camera. Additionally, the predetermined wavelength or range of wavelengths that the visor is capable of reflecting advantageously includes infrared light in this embodiment.

To track the gaze of the operator based upon a position of the operator's eyes and head, the system **20** also includes a processing element **26**. The processing element can comprise any of a number of different devices, such as a personal computer or other high level processor. As shown in FIG. 3, and as already stated, the eye-tracking assembly is capable of determining a position of the operator's eyes. Similarly, the head tracking sensor **22** is capable of determining a position of the operator's head. The processing element **26**, in turn, is capable of receiving the

position of the operator's eyes from the eye-tracking assembly and the position of the operator's head from the head tracking sensor. Based upon the position of the operator's eyes and operator's head, the processing element can determine the operator's gaze. Repeatedly receiving the position of the operator's eyes and head,
5 the processing element can therefore track the operator's gaze, as will be appreciated by those skilled in the art. And based upon the gaze of the operator the processing element can define an area of interest 38 (shown in FIG. 2) relative to an external device, such as a display.

Before the system can track the gaze of the operator, the system 20 is
10 preferably calibrated to the external device, such as a display. As previously indicated, the difficulty in calibrating conventional eye trackers is that any head movement during calibration will cause an error in the calibration. Thus, embodiments of the present invention provide a method of calibrating a gaze tracking system, such as the gaze tracking system described above, using data from the head
15 tracking sensor 22. By using data from the head tracking sensor, then, the calibration can compensate for any head movement, and the true gaze angle can be determined more accurately.

Advantageously, embodiments of the method of the present invention also uses movement of the head tracking sensor during calibration to collect eye data. In
20 this regard, conventional eye tracker calibration methods commonly calibrate the eye tracker based upon a set of calibration points that typically numbers less than ten. Conventional calibration methods, then, are typically limited to a small number of data points (i.e., input parameters) by which to approximate a calibration function for the eye tracker. As such, the more data points that are recorded, and the more
25 distributed the data points, the better the final calibration of the eye tracker. Whereas any of a number of different techniques can be employed to collect data points, embodiments of the present invention provide are capable of collecting a large number of data points during calibration, as described below.

Referring now to FIGS. 4A, 4B and 5, the method of calibrating the gaze
30 tracking system begins with initializing calibration of the gaze tracking system, as shown in block 40 of FIG. 5. Initialization can be accomplished according to any of a number of different manners but, according to one embodiment, calibration of the system is initialized by initiating a calibration routine within the processing element 26. Once calibration of the system has been initialized, the processing element can

drive a display to present a first reference point **42**, or target, within the operator's field of view, as shown in FIGS. 4A, 4B and block **44** of FIG. 5.

Once the target **42** has been presented to the operator, the operator aligns the operator's line of sight **46** with the displayed target, as shown in block **48** of FIG. 5.

5 The operator then begins the calibration process, such as by actuating the processing element **26** to begin calibration of the system. In this regard, when the operator actuates the processing element, the processing element drives the eye tracking assembly to measure the position of the operator's eyes, which measurement the processing element will then associate with the target, as shown in block **50**. At the
10 same time, the processing element drives the head tracking sensor **22** to measure the angle of the operator's head as well as translations of the position of the operator's head, as shown in block **52**. The measured angle and translations are then set by the processing element to be a second reference position.

After the position of the operator's eyes and head have been measured by the
15 gaze tracking system **20**, while keeping the operator's line of sight **46** aligned with the target **42**, the operator moves the operator's head and, thus, the head tracking sensor **22**, to a position offset from the second reference position, as shown in FIGS. 4A and 4B, and block **54** of FIG. 5. In keeping the operator's line of sight aligned with the target while the operator moves the operator's head, the operator's eyes generally
20 move opposite of the head to maintain alignment of the line of sight with the target. Once at the offset position, then, the gaze tracking system measures the position of the eyes and an angle offset of the line of sight of the eyes relative to the first reference point, as shown in block **56**. Similarly, the gaze tracking system measures the position of the head tracking sensor or, more particularly, the angle of the operator's
25 head and translations of the position of the operator's head relative to the second reference position, as shown in block **58**. Next, the processing element **26** records the positions, such as in a memory location. Also, the processing element can determine the direction of the operator's eyes relative to the operator's head from the measurements, and record the direction along with the measurements.

30 After the processing element **26** has recorded the measurements and the direction of the operator's eyes, the operator then moves the operator's head to another offset position, again keeping the line of sight **46** aligned with the target **42**. The gaze tracking system again measures the position of the eyes and head tracking sensor **22**, and records the measurements along with the direction of the operator's

eyes. The process continues for N (e.g., 300) movements of the operator's head such that the processing records N data points consisting of the recorded measurements and directions of the operator's eyes relative to the operator's head, as shown in blocks **60** and **62** of FIG. 5. Advantageously, the operator can move the operator's head to different offset positions, and the processing element can correspondingly record measurements, at a high rate, such as 60 times a second. As such, large amounts of data can be collected in a short amount of time. For example, recording measurements at a rate of 60 times a second, the processing element can record 300 measurements in five seconds. In comparison, it would require roughly ten second to collect data from a nine point grid of calibration points using conventional methods.

Allowing the operator to move the operator's head freely while aligning the line of sight **46** with the target **42** allows a large amount of data to be collected in a short amount of time. But such a method typically gives very little control over what data is collected. For example, since the operator can move his head in any way the operator chooses, the recorded data can become concentrated in a small area, such as around the target. For most calibration functions, the more distributed the data, the better the resulting calibration. Thus, to allow for more control over the data that is collected, the processing element **26** can be capable of moving the target to one or more different positions. And after moving the target to each position, the operator again aligns the line of sight and moves the head tracking sensor **22** to different offset positions, with the processing element collecting data at each position. Whereas the processing element can move the target to any one of a number of different points, the processing element preferably moves the target to areas on a reference plane (e.g., display screen) for which the processing element has fewer recorded measurements.

With the data points, then, the processing element **26** determines a calibration function to thereby calibrate the gaze tracking system **20**. The processing element can determine the calibration function according to any one of a number of different methods. For example, the processing element can determine the calibration function according to an interpolation method using an interpolation function, such as akima interpolation, b-spline interpolation, bi-cubic interpolation, linear interpolation quadratic interpolation, or the like. In such functions, the set of data points are used as reference points and intermediate points, between the data points, are determined, or interpolated, based on the surrounding data points.

According to one advantageous embodiment, the processing element determines the calibration function utilizing an artificial neural network, as illustrated in block 64 of FIG. 5. As is known to those skilled in the art, artificial neural networks are modeled upon the human brain's interconnected system of neurons. Based upon this premise, the artificial neural network allows the processing element to imitate the brain's ability to sort out patterns and learn from trial and error, discerning and extracting the relationships that underlie the input data. The network learns when the input data (with known results) is presented to processing element. Factors associated with the known results are then adjusted to bring the calibration output closer to the known result (e.g., position relative to the target).

In addition to the above identified methods of determining the calibration function, the processing element can use known physical properties of the optics of the eye tracking assembly 24 of the gaze tracking system 20, and/or the physical properties of the operator's eyes (e.g., curvature of the eyes), to determine the calibration function. In this regard, the above methods of determining the calibration function allow for any unknown distortion to be present in the input data. For example, due to the curvature of the visor 32, the image capture device 30 may receive and/or record an image of the pupils of the operator's eyes that has some degree of radial distortion. Embodiments of the calibration method of the present invention can at least partially compensate for the distortion by estimating the calibration function for the data. However, using the known physical properties of the optics, the processing element can further compensate for any optical distortion. For example, the processing element can further compensate for optical distortion by computing the light path through the system and mapping out any irregularities according to any of a number of known techniques.

Referring now to FIG. 6, a visual display system 70, such as a flight simulation system, that would benefit from the gaze tracking system of the present invention is illustrated. The visual display system generally includes a plurality of display screens 72. For example, the visual display system can include an out-the-window flight simulation system such as the Visual Integrated Display System manufactured by The Boeing Company, the assignee of the present application. As also illustrated in FIG. 6, the image displayed on the display screens 72 includes a background image having a predetermined size and resolution. The background image is generally generated by a background image projector. The background

image projector can, and preferably does, include a plurality of background image projectors, at least one of which is associated with each display screen. For full color background images, the background image projectors are generally RGB projector.

5 In order to display a relatively large background image for the operator, the individual pixels are projected, and thereby expanded, for display on the associated display screen 72. For example, each pair of video lines typically defines a projection angle of 7 to 12 arcminutes. Therefore, the resulting background image displayed on the display screens has a relatively low resolution. As illustrated in FIG. 6, an inset image 74 can also be displayed on the display screen and is generally generated by an inset image projector. As shown, the inset image can include other aircraft in an area of interest (AOI) 76 of the operator. Each inset image (i.e., AOI image) preferably has a smaller size and a higher resolution than the background image in order to provide the operator with additional detail in this particular AOI. The AOI is defined by the gaze of the operator and, as such, the visual display system includes a gaze tracking system, such as a gaze tracking system 20 in accordance with the present invention (shown in FIGS. 2 – 4), to track the gaze of the operator. For more information on such a display system, see U.S. Patent No. 5,487,665 or U.S. Patent No. 5,746,599.

20 Therefore, the present invention provides an improved eye-tracking assembly, gaze tracking system and method of calibration. In this regard, by including a visor, at least a portion of which is capable of being located outside the field of view of the operator, the operator can utilize the eye-tracking assembly without distractions associated with conventional eye-tracking assemblies. As such, the visor of the eye-tracking assembly can provide a more native environment to an operator, particularly in instances in which the operator would typically wear a visor that encompasses the operator's field of view. Also, the present invention provides an improved method of calibrating a gaze tracking system. The method of calibration includes movement of the head tracking sensor with the operator's eyes aligned in a particular direction, as opposed to fixing the head in position and aligning the operator's line of sight with several reference points. As such, the method provides a more accurate technique for calibrating the gaze tracking system. Further, the method can utilize an artificial neural network to calibrate the system based upon input data from an eye-tracking

assembly and head tracking sensor, which allows the neural network to adaptively learn from previous movements.

Many modifications and other embodiments of the invention will come to mind to one skilled in the art to which this invention pertains having the benefit of the teachings presented in the foregoing descriptions and the associated drawings.
5 Therefore, it is to be understood that the invention is not to be limited to the specific embodiments disclosed and that modifications and other embodiments are intended to be included within the scope of the appended claims. Although specific terms are employed herein, they are used in a generic and descriptive sense only and not for
10 purposes of limitation.

**THE EMBODIMENTS OF THE INVENTION IN WHICH AN EXCLUSIVE
PROPERTY OR PRIVILEGE IS CLAIMED ARE DEFINED AS FOLLOWS:**

- 5 1. A head-mounted eye tracking assembly for tracking movement of at least one
eye of an operator, said eye tracking assembly comprising:
- 10 a visor having an arcuate shape including a concave surface and an
opposed convex surface, wherein said visor is capable of being
disposed such that the at least one eye is located proximate the concave
surface, wherein said visor is at least partially reflective such that said
visor is capable of reflecting an image of the at least one eye, and
wherein said visor is capable of being disposed such that at least a
portion of said visor is located outside a field of view of the operator;
and
- 15 an image capture device disposed proximate the concave surface of
said visor, wherein said image capture device is capable of tracking
movement of the at least one eye based upon the image of the at least
one eye reflected by said visor.
- 20 2. A head-mounted eye tracking assembly according to Claim 1, wherein the
concave surface of said visor includes a reflective coating.
- 25 3. A head-mounted eye tracking assembly according to Claims 1 or 2, further
comprising an illuminator capable of illuminating the at least one eye.
4. A head-mounted eye tracking assembly according to Claim 3, wherein said
illuminator is capable of illuminating the at least one eye with infrared light.
- 30 5. A head-mounted eye tracking assembly according to any one of Claims 1 to 4
further comprising a lens disposed in an optical path of said image capture
device, wherein an effective focus of said image capture device is based upon
an optical power of said visor and an optical power of said lens.

6. A head-mounted eye tracking assembly according to any one of Claims 1 to 5, wherein said image capture device is located outside the field of view of the operator.

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7. A system for tracking a gaze of an operator, said gaze tracking system comprising:

a head-mounted eye tracking assembly comprising:

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a visor having an arcuate shape including a concave surface and an opposed convex surface, wherein said visor is capable of being disposed such that at least one eye is located proximate the concave side, wherein said visor is at least partially reflective such that said visor is capable of reflecting an image of the at least one eye, wherein said visor is capable of being disposed such that at least a portion of said visor is located outside a field of view of the operator, and wherein the head-mounted eye tracking assembly is capable of repeatedly determining a position of the at least one eye based upon the image of the at least one eye reflected by said visor to thereby track movement of the at least one eye;

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a head-mounted head tracking sensor capable of repeatedly determining a position of the head to thereby track movement of the head, wherein each position of the head is associated with a position of the at least one eye; and

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a processing element capable of repeatedly determining the gaze of the operator to thereby track the gaze of the operator, wherein said processing element repeatedly determines the gaze of the operator based upon each position of the head and the associated position of the at least one eye.

8. A system according to Claim 7, wherein the concave surface of the visor of said head-mounted eye tracking assembly includes a reflective coating.
- 5 9. A system according to Claims 7 or 8, wherein said head-mounted eye tracking assembly further comprises an illuminator capable of illuminating the at least one eye.
- 10 10. A system according to Claim 9, wherein the illuminator is capable of illuminating the at least one eye with infrared light.
- 15 11. A system according to any one of Claims 7 to 10, wherein said head-mounted eye tracking assembly further comprises an image capture device disposed proximate the concave surface of said visor, and wherein the image capture device is capable of tracking movement of the at least one eye based upon the image of the at least one eye reflected by said visor.
- 20 12. A system according to Claim 11, wherein said head-mounted eye tracking assembly further comprises a lens disposed in an optical path of the image capture device, wherein an effective focus of the image capture device is based upon an optical power of the visor and an optical power of the lens.
- 25 13. A system according to Claims 11 or 12, wherein the image capture device is located outside the field of view of the operator.
- 30 14. A visual display system comprising:

a background image projector having a predetermined field of view, said background image projector generating a background image having a predetermined size and resolution that at least partially fills the field of view;

at least one inset image projector for generating an area of interest (AOI) image having a smaller size and a higher resolution than the

background image, said inset image projector having a predetermined field of view that is capable of being movably disposed at least partially within the field of view of said background image projector; and

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a gaze tracking system capable of directing the movement of the field of view of said inset image projector based upon the direction in which an operator is looking, said gaze tracking system comprising a head-mounted eye tracking assembly comprising:

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a visor having an arcuate shape including a concave surface and an opposed convex surface, wherein said visor is capable of being disposed such that at least one eye is located proximate the concave surface, wherein said visor is at least partially reflective such that said visor is capable of reflecting an image of the at least one eye, and wherein said visor is capable of being disposed such that at least a portion of said visor is located outside a field of view of an operator; and

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an image capture device disposed proximate the concave surface of said visor, wherein said image capture device is capable of tracking movement of the at least one eye based upon the image of the at least one eye reflected by said visor.

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15. A visual display system according to Claim 14, wherein said gaze tracking system further comprises:

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a head-mounted head tracking sensor capable of repeatedly determining a position of the head to thereby track movement of the head, wherein each position of the head is associated with a position of the at least one eye; and

a processing element capable of repeatedly determining a gaze of the operator to thereby track the gaze of the operator, wherein said processing element repeatedly determines the gaze of the operator based upon each position of the head and the associated position of the at least one eye.

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- 16.** A visual display system according to Claims **14** or **15**, wherein the concave surface of the visor of said head-mounted eye tracking assembly includes a reflective coating.

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- 17.** A visual display system according to any one of Claims **14** to **16**, wherein said head-mounted eye tracking assembly further comprises an illuminator capable of illuminating the at least one eye.

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- 18.** A visual display system according to any one of Claims **14** to **17**, wherein said head-mounted eye tracking assembly further comprises a lens disposed in an optical path of said image capture device, wherein an effective focus of said image capture device is based upon an optical power of said visor and an optical power of said lens.

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- 19.** A head-mounted eye tracking assembly for tracking movement of at least one eye of an operator, said eye tracking assembly comprising:

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a visor having an arcuate shape including a concave surface and an opposed convex surface, wherein said visor is capable of being disposed such that the at least one eye is located proximate the concave surface, wherein said visor is at least partially reflective such that said visor is capable of reflecting an image of the at least one eye, and wherein said visor is capable of being disposed such that at least a portion of said visor is located outside a field of view of the operator;

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an image capture device disposed proximate the concave surface of said visor, wherein said image capture device is capable of tracking

movement of the at least one eye based upon the image of the at least one eye reflected by said visor; and

5 a lens disposed in an optical path of said image capture device wherein an effective focus of said image capture device is based upon an optical power of said visor and an optical power of said lens.

- 10 20. A head-mounted eye tracking assembly according to claim 19, wherein the concave surface of said visor includes a reflective coating.
21. A head-mounted eye tracking assembly according to claim 19, further comprising an illuminator capable of illuminating the at least one eye.
- 15 22. A head-mounted eye tracking assembly according to claim 21, wherein said illuminator is capable of illuminating the at least one eye with infrared light.
23. A head-mounted eye tracking assembly according to claim 19, wherein said image capture device is located outside the field of view of the operator.
- 20 24. A head-mounted eye tracking assembly according to claim 19, wherein said visor is capable of reflecting an image of a pupil of at least one eye, and wherein said image capture device is capable of tracking movement of the at least one eye based upon the image of the pupil of the at least one eye.
- 25 25. A system for tracking a gaze of an operator, said gaze tracking system comprising:

a head-mounted eye tracking assembly comprising:

30 a visor having an arcuate shape including a concave surface and opposed an convex surface, wherein said visor is capable of being disposed such that the at least one eye is located proximate the concave side, wherein said visor is at least

5 partially reflective such that said visor is capable of reflecting
an image of the at least one eye, wherein said visor is capable
of being disposed such that at least a portion of said visor is
located outside a field of view of the operator, and wherein the
head-mounted eye tracking assembly is capable of repeatedly
determining a position of the at least one eye based upon the
image of the at least one eye reflected by said visor to thereby
track movement of the at least one eye;

10 an image capture device disposed proximate the concave
surface of said visor, wherein the image capture device is
capable of tracking movement of the at least one eye based
upon the image of the at least one eye reflected by said visor;
and

15 a lens disposed in an optical path of the image capture device,
wherein an effective focus of the image capture device is based
upon an optical power of the visor and an optical power of the
lens;

20 a head-mounted head tracking sensor capable of repeatedly determining a
position of the head to thereby track movement of the head, wherein each
position of the head associated with a position of the at least one eye; and

25 a processing element capable of repeatedly determining the gaze of the
operator to thereby track the gaze of the operator, wherein said processing
element repeatedly determines the gaze of the operator based upon each
position of the head and the associated position of the at least one eye.

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- 26.** A system according to claim **25**, wherein the concave surface of the visor of
said head-mounted eye tracking assembly includes a reflective coating.

27. A system according to claim 25, wherein said head-mounted eye tracking assembly further comprises an illuminator capable of illuminating the at least one eye.
- 5 28. A system according to claim 27, wherein the illuminator is capable of illuminating the at least one eye with infrared light.
29. A system according to claim 25, wherein the image capture device located outside the field of view of the operator.
- 10 30. A system according to claim 25, wherein said visor is capable of reflecting an image of a pupil of at least one eye, and wherein the head-mounted eye tracking assembly is capable of repeatedly determining a position of the at least one eye based upon the image of the pupil of the at least one eye.
- 15 31. A visual display system comprising:
- a background image projector having a predetermined field of view, said background image projector generating a background image
- 20 having a predetermined size and resolution that at least partially fills the field of view;
- at least one inset image projector for generating an area of interest (AOI) image having a smaller size and a higher resolution than the
- 25 background image, said inset image projector having a predetermined field of view that is capable of being movably disposed at least partially within the field of view of said background image projector; and
- 30 a gaze tracking system capable of directing the movement of the field of view of said inset image projector based upon the direction in which an operator is looking, said gaze tracking system comprising a head-mounted eye tracking assembly comprising:

5 a visor having an arcuate shape including a concave surface and
an opposed convex surface, wherein said visor is capable of
being disposed such that the at least one eye is located
proximate the concave surface, wherein said visor is at least
partially reflective such that said visor is capable of reflecting
an image of the at least one eye, and wherein said visor is
capable of being disposed such that at least a portion of said
visor is located outside a field of view of the operator;

10

an image capture device disposed proximate the concave
surface of said visor, wherein said image capture device is
capable of tracking movement of the at least one eye based
upon the image of the at least one eye reflected by said visor;

15

a lens disposed in an optical path of said image capture device,
wherein an effective focus of said image capture device is
based upon an optical power of said visor and an optical power
of said lens.

20

32. A visual display system according to claim **31**, wherein said gaze tracking
system further comprises:

25

a head-mounted head tracking sensor capable of repeatedly
determining a position of the head to thereby track movement of the
head, wherein each position of the head is associated with a position of
the at least one eye; and

30

a processing element capable of repeatedly determining the gaze of the
operator to thereby track the gaze of the operator, wherein said
processing element repeatedly determines the gaze of the operator
based upon each position of the head and the associated position of the
at least one eye.

- 5
- 10
- 15
- 20
- 33.** A visual display system according to claim **31**, where the concave surface of the visor of said head-mounted eye tracking assembly includes a reflective coating.
- 34.** A visual display system according to claim **31**, wherein said head-mounted eye tracking assembly further comprises an illuminator capable of illuminating the at least one eye.
- 35.** A visual display system according to claim **31**, wherein said head-mounted eye tracking assembly further comprises a lens disposed in an optical path of said image capture device, wherein an effective focus of said image capture device is based upon an optical power of said visor and an optical power of said lens.
- 36.** A visual display system according to claim **31**, wherein said visor is capable of reflecting an image of a pupil of at least one eye, and wherein said image capture device is capable of tracking movement of the at least one eye based upon the image of the pupil of the at least one eye.
- 37.** A visual display system according to claim **31**, wherein said inset image projector has a predetermined field of view that is capable of being movably disposed based upon electronic raster deflection.

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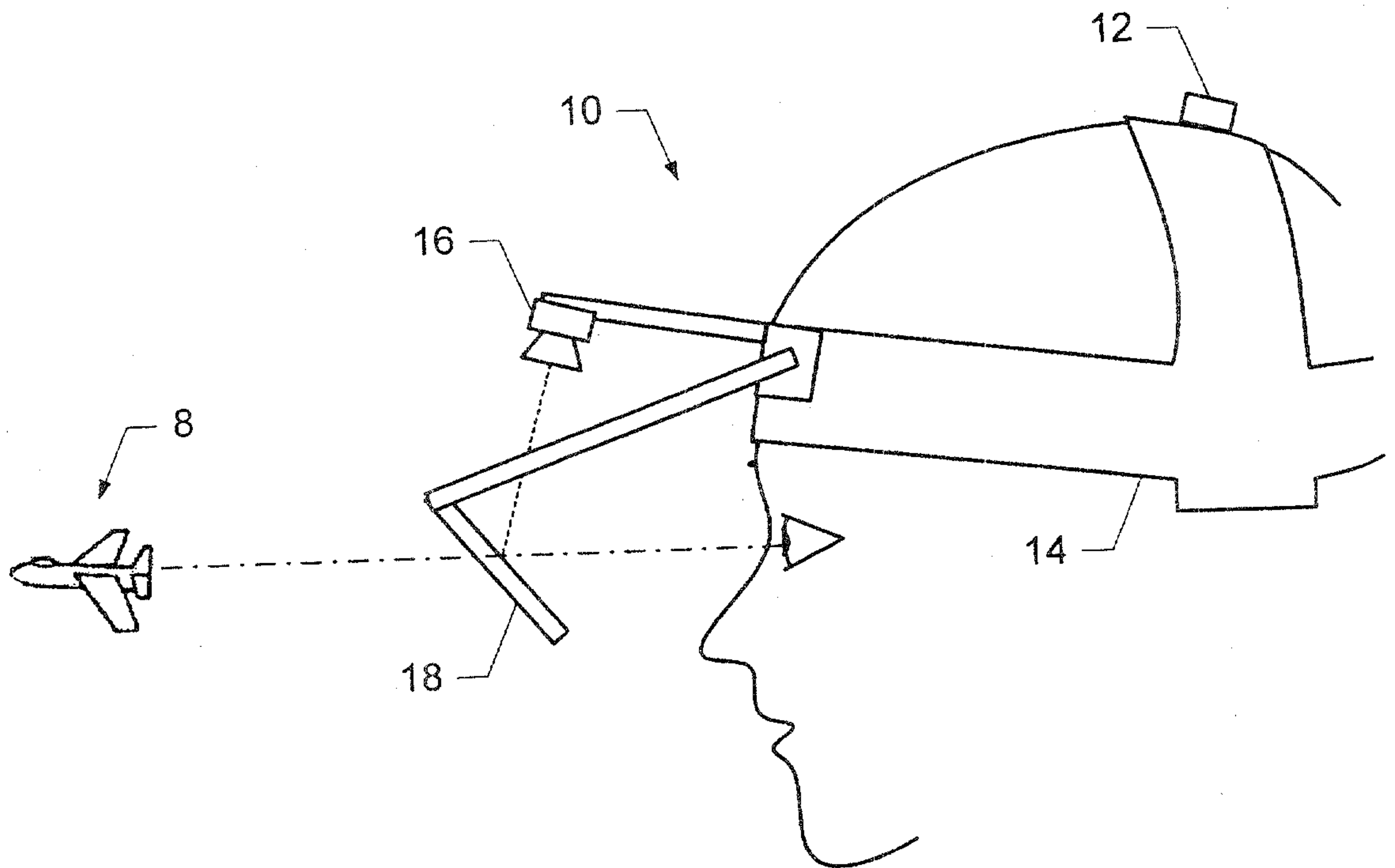


FIG. 1.
(PRIOR ART)

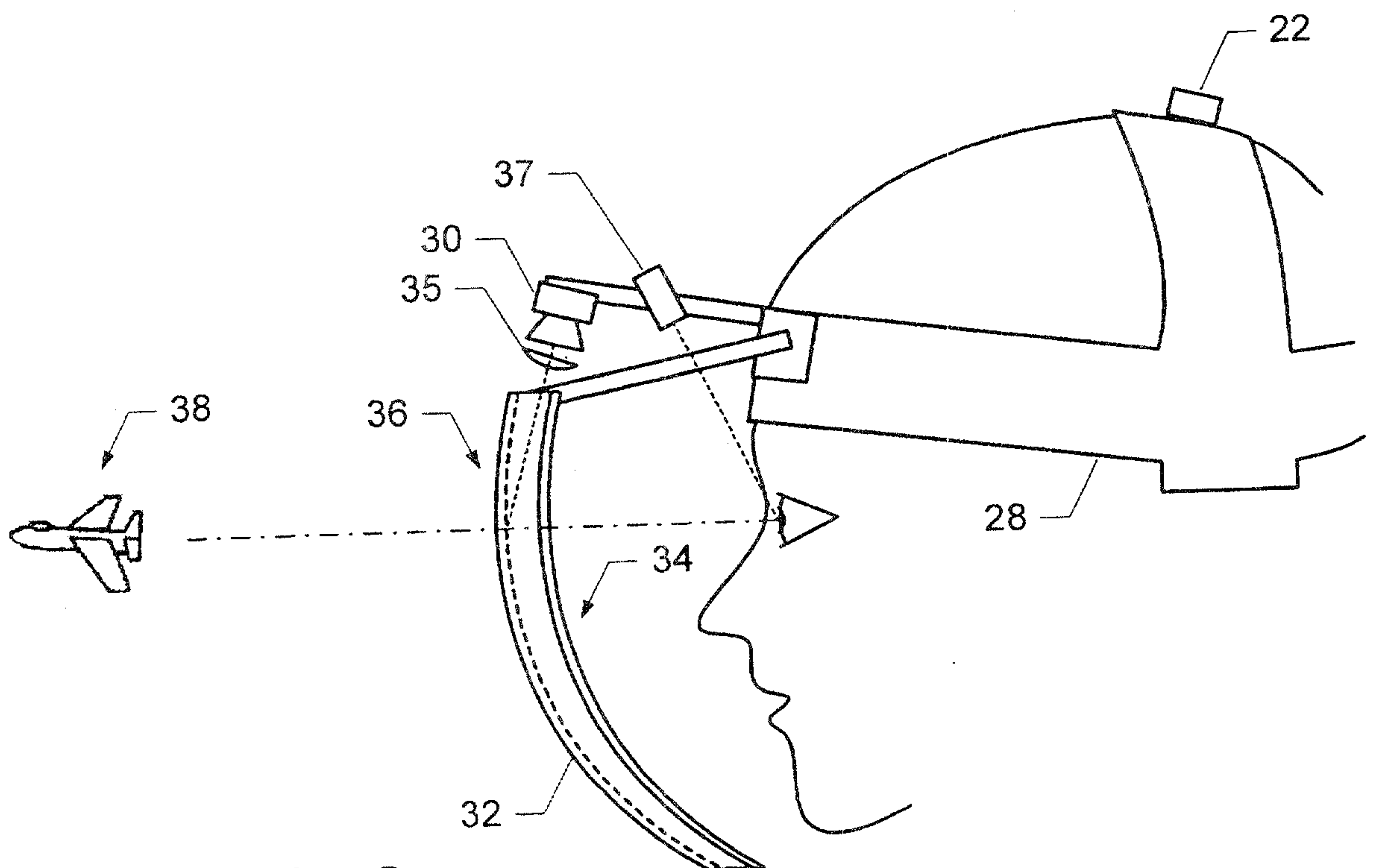
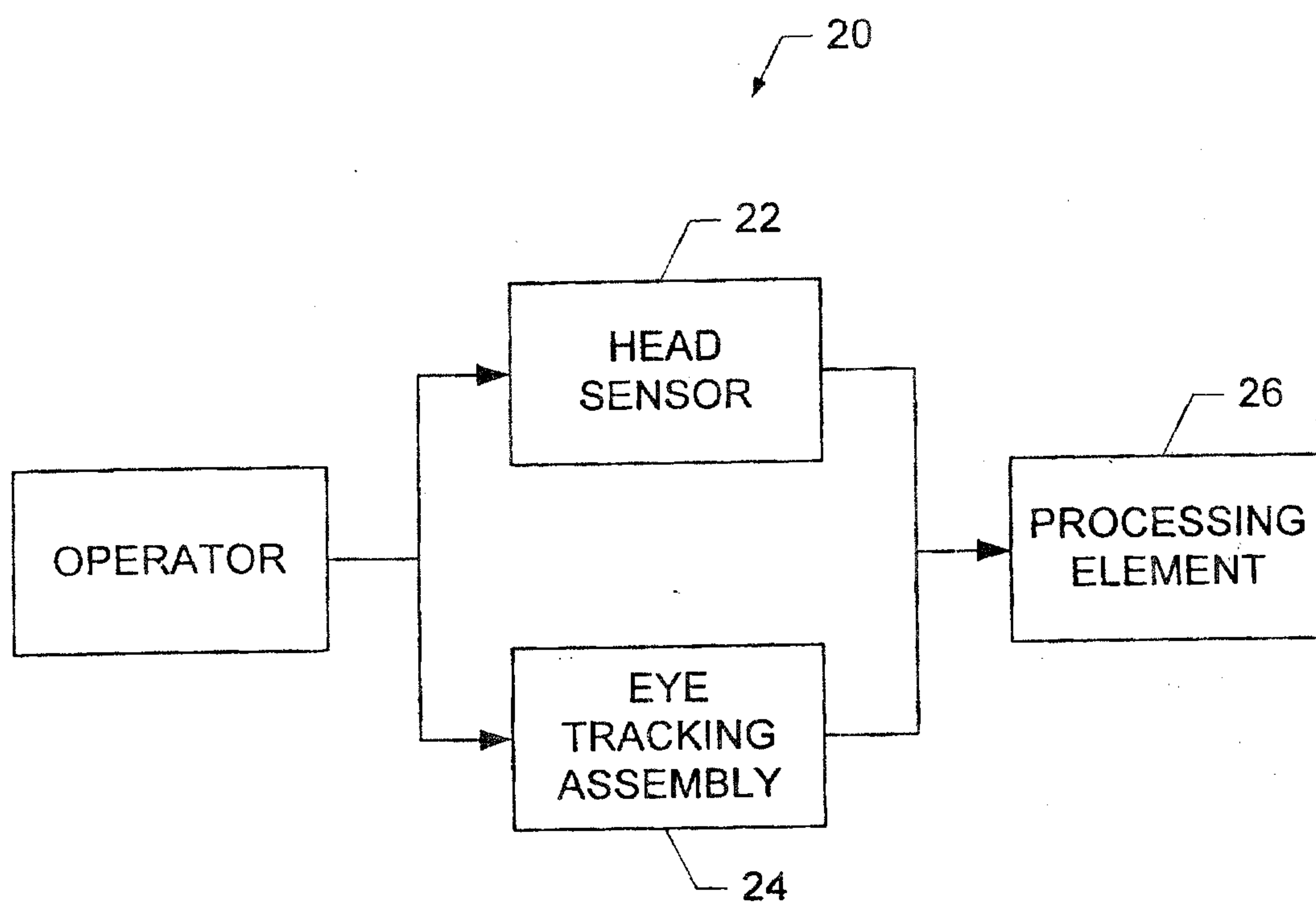
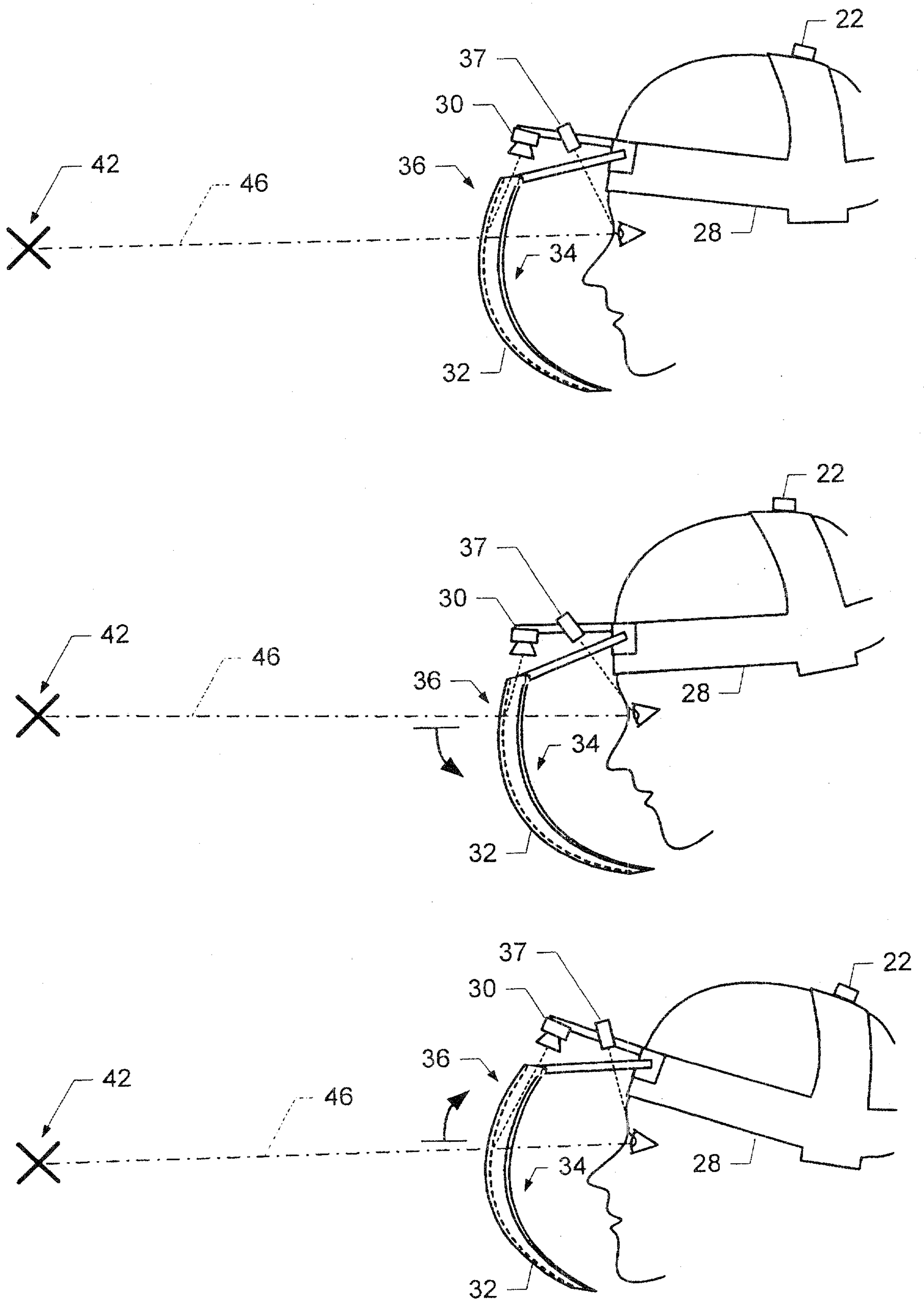


FIG. 2.

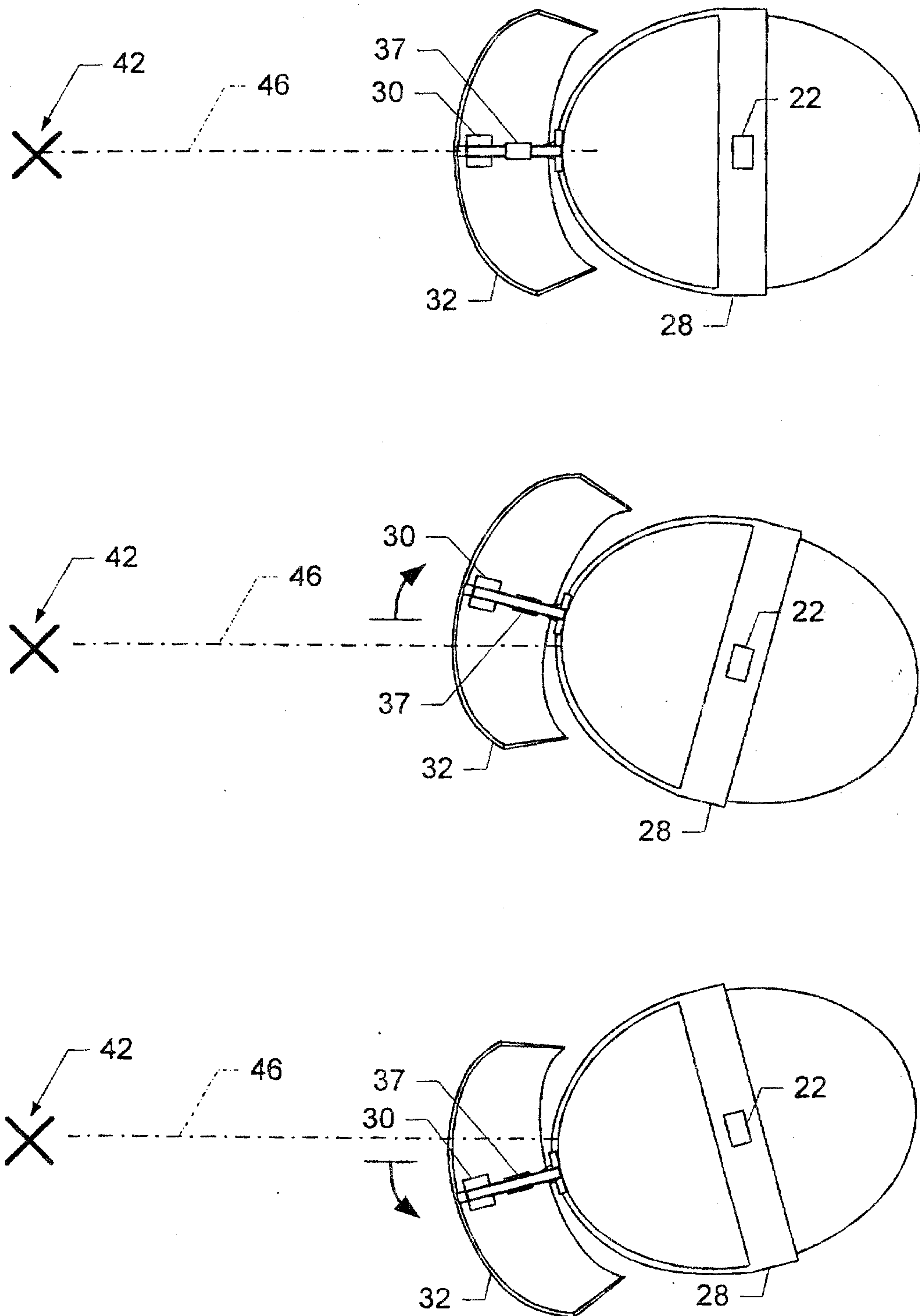
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FIG. 3.

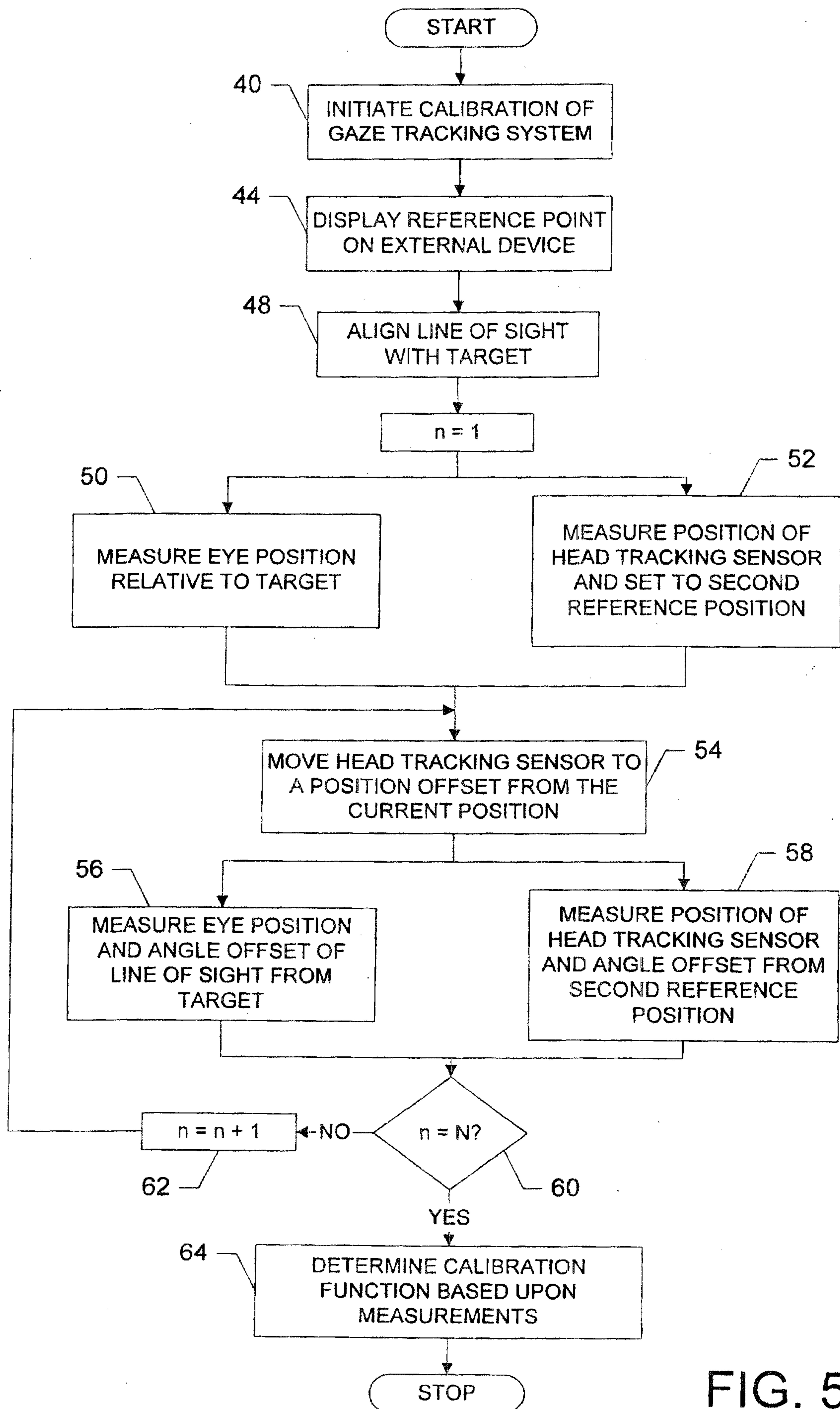
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FIG. 4A.

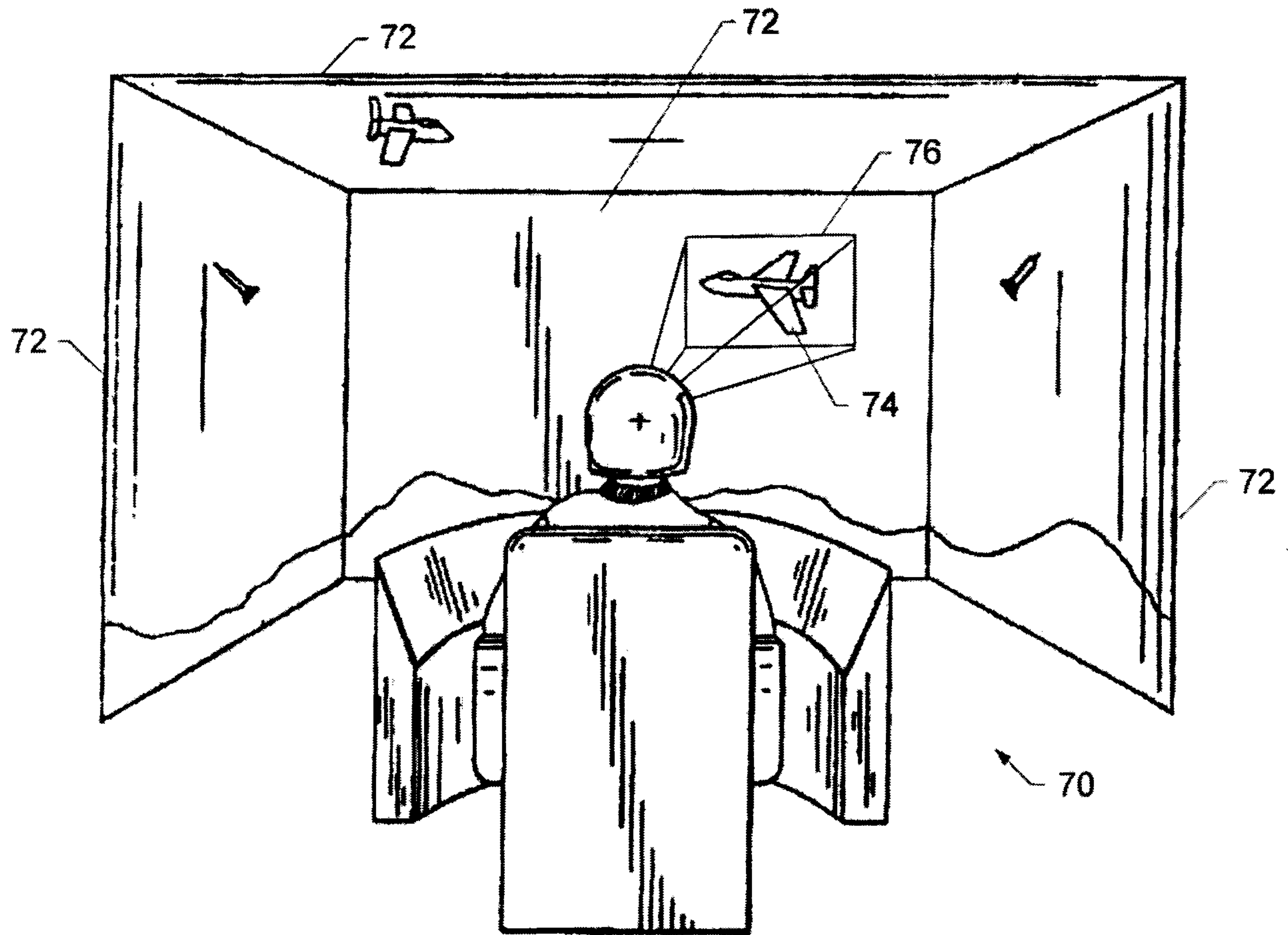
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FIG. 4B.

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FIG. 5.

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FIG. 6.

