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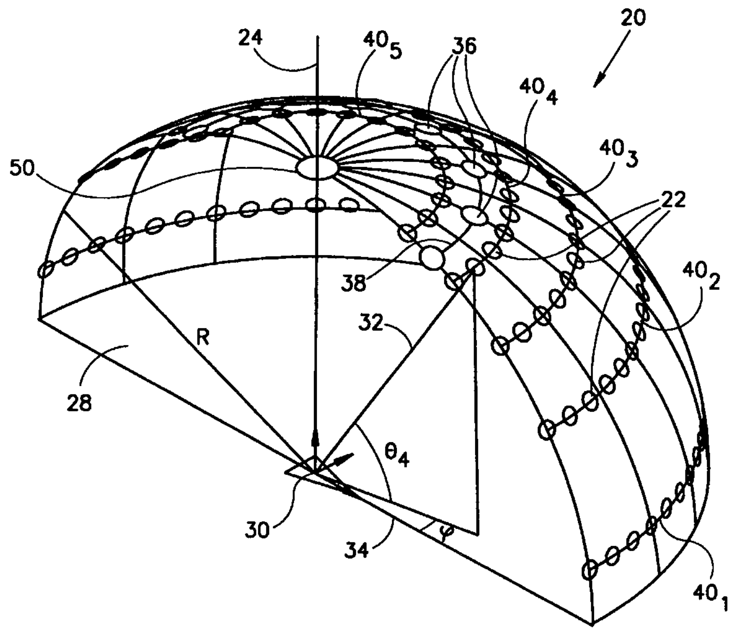

(57) Abstract

An illumination system is disclosed for use in visual inspection of articles placed in an inspection volume comprising a plurality of light sources and a light source control system, wherein light from each of the plurality of light sources illuminates a same central inspection point in the inspection volume and the light source control system controls the intensity of light emitted by any one of the plurality of light sources independently of the intensity of light emitted by any of the other of the plurality of light sources.

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ILLUMINATION SYSTEM FOR OBJECT INSPECTION

FIELD OF THE INVENTION

The present invention relates to illumination systems and in particular to illumination systems used in visual inspection of articles for quality control.

BACKGROUND OF THE INVENTION

Visual inspection systems for quality control are used for verifying that dimensions of inspected articles, or of features of these articles, meet required specifications and tolerances, that the articles are free from structural defects, and/or that the quality and integrity of their surfaces meet predetermined standards.

In such systems the illumination of the article inspected is of prime importance. If the product is not properly illuminated, details that the visual inspection process should notice might be overlooked. Modern illumination systems often have to provide illumination of intricate and complicated articles that are moved to an inspection station by automatic conveyence. The orientation of these articles with respect to the inspection system varies, and they are generally in the inspection station for a short period of time. An illumination system that can provide adequate illumination for inspecting articles under these circumstances should be able to quickly change and set the intensity and directional configuration of the light with which it illuminates inspected articles with a high degree of resolution.

For example, a fissure in a surface of an inspected article might not be visible with intense direct lighting perpendicular to the surface in which the fissure is found. However, with slightly off angle illumination, at reduced intensity, one of the edges of the fissure might reflect sufficiently more light than the other to provide enough contrast in the light reflected along the fissure so that the fissure becomes visible. Similarly, the size and condition of a polished surface of an inspected article generally reflects light specularly. It is very difficult to properly inspect such a surface without fine adjustment of light intensity and direction.

Many prior art illumination systems do not have sufficient flexibility to respond to these needs of present day visual inspection systems. One illumination system, described in US patent 5,519,496 to Gerald D. Borgert et al, provides for illumination of an inspected article with beams of light produced by light banks comprising a plurality of LEDs mounted on flat panels. The panels are mounted in fixed positions in the illumination system architecture and the light banks illuminate an article from only a small number of different directions.

The above described system and others sometimes rely on mechanical means to orient an article under inspection. Mechanical orientation systems are generally slow and expensive. Other illumination systems, which use annular light sources, tend to have poor ability to discriminate specific areas of interest for illumination from surrounding areas of an article being inspected.

It is therefore desirable to have an illumination system with improved control of the direction and intensity of the light with which it illuminates articles undergoing visual inspection.

SUMMARY OF THE INVENTION

It is an object of some embodiments of the present invention to provide an illumination system comprising an array of light sources in a fixed architecture of simple construction, hereafter an "illumination array", that can illuminate different orientations, contours, and surface features of an article positioned in an inspection zone for the purposes of visual inspection with beams of light having finely controlled directions and intensities.

It is an object of some aspects of preferred embodiments of the present invention to provide illumination of the article with one or more light beams, where a light beam is substantially defined by the position of the source of the light beam, a central light ray in the light beam and a beam opening angle, and where the central ray of each light beam is incident on the article from a different angle, hereafter "beam incident angle", with respect to a set of coordinate axes with origin at or near to the article.

It is a further object of other aspects of preferred embodiments of the invention to provide, for substantially any given desired angle of incidence of light on a surface region of the article, a light beam with beam incident angle that differs from the desired angle of incidence of light by a substantially small angle without moving the article.

A further object of another aspect of preferred embodiments of the present invention is to enable fine adjustment of the intensity of light incident on the object at a given beam incident angle, independent of the intensity of the light incident on the article at other beam incident angles.

It is an object of other aspects of the present invention to provide illumination configurations, wherein an illumination configuration comprises a configuration origin and direction, measured from convenient coordinate axes, which defines the position of the illumination configuration, and a set of light beams having a particular spatial distribution with respect to the configuration origin and direction, wherein each light beam radiates light at a particular output intensity.

It is a further object of some aspects of the present invention to provide for moving an illumination configuration from one point in space to another point in space so that a same illumination configuration illuminates an article from different spatial positions.

A further object of another aspect of the invention is to provide illumination configurations of light beams from closely spaced light sources which overlap to illuminate a same region of an article with light at beam incident angles differing by small angles.

An aspect of some embodiments of the present invention concerns illumination of articles exhibiting spatial symmetries. Many manufactured articles exhibit geometrical symmetries of one type or another. N-fold rotational symmetries about an axis of rotation with N = 2,3,4,6, and 12 are common. An object with an N-fold rotational symmetry about an axis of rotation appears identical when viewed from any one of two viewing angles, where the difference between the viewing angles is an angle of rotation about the axis of rotation which is an integer multiple of $360^{o}/N$. For example an object with a 3-fold rotational symmetry about an axis of rotation looks the same when viewed from a point with an elevation angle and azimuth angle, θ and φ respectively, and from points with the same elevation angle but azimuth angles of $\varphi+120^{o}$ and $\varphi+240^{o}$.

Illumination arrays having symmetries, in accordance with a preferred embodiment of the present invention, are particularly well adapted to illuminate articles having geometries with symmetries that match those of the illumination array. For example, an illumination array with an N-fold rotational symmetry about an axis of rotation, in accordance with a preferred embodiment of the present invention, can optimally illuminate articles with n-fold rotational symmetries, where n is equal to any factor of N. This can be accomplished because the illumination array can illuminate such articles with exactly a same illumination configuration from directions rotated with respect to each other by angles which are multiples of $360^{o}/N$. The array can also very effectively illuminate articles with rotational symmetries which are multiples of N or which share a common factor with N.

Another aspect of some embodiments of the invention relates to accommodating different orientations of articles in an inspection zone. Articles moving into and out of an inspection station are often not positioned with high precision in an inspection zone of the inspection station. The process by which the article is moved into the inspection zone frequently randomizes the article's orientation. It is advantageous for an illumination system to be able to change the direction and intensity of illumination with a high degree of resolution in order to adjust to the varying orientation of the article and illuminate the article along a desired direction of the article's geometry. Preferably, a CCD camera is used to detect the orientation of the article in the inspection zone. The direction and intensity of the illumination is then adjusted in accordance with the detected orientation. Individual control of light sources, in accordance with a preferred embodiment of the present invention, is effective in accomplishing this.

Another object of some embodiments of the present invention is to provide a user interface for controlling the illumination system which interface comprises a feedback display that shows how a particular article in the inspection zone is illuminated.

In a preferred embodiment of the present invention, a plurality of substantially monochromatic light sources are positioned at fixed locations in an illumination array so that light beams which they project preferably illuminate the same volume of space, hereafter a "focal volume". Preferably, each light source can be turned on or off independently of the other light sources. Preferably, the output intensity with which each light source radiates light can be set to an output intensity value in a range values preferably independent of the output intensity settings of other light sources in the illumination array.

The number of the plurality of the light sources, and their spatial distribution in the illumination array is preferably such so that an article placed in the focal volume can be appropriately illuminated for visual inspection without having to move the article.

Preferably, the light sources are high intensity monochromatic LEDs. LEDs have very fast rise times, on the order of nanoseconds. These fast rise times enable rapid turn-on and stabilization of illumination configurations and thereby very rapid switching between different illumination configurations. As a result, illumination patterns can be changed and stabilized in time periods (that include processing time for a LED controller) which are on the order of milliseconds. These time periods are short enough so that an illumination system in accordance with a preferred embodiment of the present invention can change illumination patterns at a frequency that matches frame acquisition frequencies of typical imaging systems used in visual inspection systems. Different features of an inspected article can be sequentially highlighted for examination rapidly and inspection of an article can be accomplished with reduced inspection times. Fluorescent lights and PL bulbs have switching and stabilization times on the order of seconds to minutes respectively and are not capable of providing fast switched illumination patterns.

Preferably, the LEDs have focusing lenses so that they radiate narrow angle beams of light. Beam half angles, at 90% of maximum intensity, are preferably on the order of 10^{o} to 20^{o}, preferably, 14^{o}. A diffusing filter is positioned between the LEDs and an article in a focal volume being illuminated in some preferred embodiments of the invention in order to reduce unwanted specular reflection from the article and to blur out the point like structure of the LED light sources. Preferably, the diffusing filter is formed in the shape of a shell of revolution. Preferably, the intensity of light output from each LED can be accurately set and monitored, preferably, at one of at least 256 different output intensities within the dynamic range of the light output intensity of the LED.

For color inspection of an article or features of an article, an illumination system in accordance with a preferred embodiment of the present invention preferably comprises additional light sources which illuminate the focal volume with substantially white light. Alternatively, or additionally, color inspection can be accomplished by combining light from LEDs which illuminate an article with different wave lengths of light. For example, LEDs emitting blue, green and red light, with individually controlled output intensities, can be used to color inspect an article with different color tones.

In one preferred embodiment of the invention, the LEDs are positioned on one side of a plane which passes through the focal volume. Preferably, the LEDs are mounted to a surface of revolution, hereafter an "illumination dome", so that light beams which they emit illuminate regions inside the illumination dome. Preferably, the surface of revolution is generated by an arc of a circle. Preferably, the arc subtends less than 180^{o} to the center of the circle. Preferably the surface is generated by rotating the arc through 180^{o} about an axis through the center of the circle that bisects the arc. A focal point of the illumination dome is the center of this circle.

Preferably, the LEDs are positioned along a multiplicity of circles, hereafter "LED rings", substantially coincident with circles formed by the intersection of planes perpendicular to the axis of rotation of the illumination dome and the the illumination dome. Preferably, the LEDs are aligned so that they have a focal volume which is substantially centered on the focal point of the illumination dome. A focal plane of the illumination dome is the plane through the focal point perpendicular to the axis of rotation of the illumination dome.

The number of LEDs in any LED ring is preferably a multiple of an integer, N, (N>1), where the same integer is used for each ring. Preferably, the arc length between any two adjacent LEDs on a LED ring is the same. This endows the illumination array with an N-fold rotational symmetry about the axis of the illumination dome. Preferably, N is a multiple of 12. This assures that the illumination array will have n-fold rotational symmetries for n= 2, 3, 4, 6, and 12.These n-fold symmetries can be very useful for the proper illumination of manufactured articles which often have rotational symmetries of 2, 3, 4, 6, and 12. In order to properly inspect an article having rotational symmetry it might be necessary to illuminate the article with light incident at an angle with respect to an axis of the product, and then step rotate the lighting around the axis by an angle that matches the rotational symmetry of the product. A high degree of rotational symmetry is also useful if the light array is to accommodate different rotational orientations of articles placed in the focal volume, especially when the orientation of the articles is randomized in the process of bringing the article into the focal volume.

We now define the angle of elevation of a LED ring to be the angle that a line, from the focal point to a point on the LED ring, makes with the focal plane. Let the position of a LED in a LED ring be defined the elevation angle of the LED ring and by an azimuth angle measured from a convenient line in the focal plane.

Preferably, the length of the arc between a LED and a LED adjacent to it on a LED ring is identical for all the LED rings. The length of this arc determines the elevation angles of the LED rings as a function of the number of LEDs in a ring. Let n_1 be the number of LEDs in the largest LED ring, and n_i the number of LEDs in the i^{th} LED ring, and assume that n_1 and all the n_i are multiples of a same integer N greater than 1 (for N-fold symmetry). Then in order for the arc length between adjacent LEDs on all LED rings to be the same, the elevation angle θ_i, of the i^{th} LED ring must be chosen so that $\cos\theta_i = (n_i/n_1)\cos\theta_1$ where θ_1 is the elevation angle of the largest LED ring.

In accordance with a preferred embodiment of the present invention, for very large numbers of LED rings, and LEDs per LED ring, the difference in the number of LEDs between adjacent LED rings in the region of elevation angle θ is preferably approximately N x $(\sin\theta/\sin\theta_1)$, where N is the order of the N-fold rotational symmetry of the illumination array, and θ_1 is the elevation of the largest LED ring. For this configuration, the number of LEDs per solid angle at any elevation angle and azimuth angle is then approximately the same.

Preferably, the illumination dome comprises at least five LED rings. Preferably, the largest ring is at or near to the rim of the half dome at an elevation angle substantially equal to about 15^o, and with the azimuthal difference between adjacent LEDs on the largest ring substantially equal to 5^o.

Preferably, the focal volume and the field of a view of a visual image acquisition system, such as a CCD camera, are substantially congruent. A hole in the illumination dome surface centered on the axis of rotation of the illumination dome is preferably used for a viewing portal for the image acquisition system.

An illumination system comprising an illumination array of LEDs in accordance with a preferred embodiment of the present invention preferably comprises a LED control system having a user interface that displays graphically, on a video console, which LEDs in the illumination array are off and which are on at any one time. Preferably, an article, in the focal volume, which is illuminated by those LEDs which are on, is also displayed so that a user can set the light output intensities of LEDs in the illumination array in response to the displayed illumination of the article. Preferably, this can be done by interacting with the video display.

Preferably, the LED control system enables the user to define illumination configurations and apply them to the LEDs in the illumination array.

An illumination configuration is preferably defined by determining a set of m LED configuration positions, which are LED positions defined by coordinates measured relative to a convenient configuration origin and configuration coordinate axes, where m is a desired number of light beams to be used in the illumination configuration. Each of the m LED configuration positions is preferably assigned a light output intensity.

Applying an illumination configuration preferably comprises assigning coordinates to its configuration origin and directions to its coordinate axes and then for each LED configuration position in the set of n LED configuration positions of the illumination configuration, turning on a LED located at or closest to the LED configuration position so that it radiates light at the output intensity assigned to the LED configuration position. Preferably, turning on the LEDs at or near to the LED configuration positions and setting their output intensities is done automatically by the LED control system once the coordinates of the configuration origin and the directions of the configuration axes are assigned. An illumination configuration is thereby easily moved from position to position in the illumination array by changing the coordinates and directions assigned to its configuration origin and coordinates axes respectively.

Preferably, an illumination configuration comprises a configuration intensity parameter. Preferably, the user can simultaneously increase or decrease the light output intensities of each of the LEDs in a group of LEDs whose light output intensities are set by an illumination configuration by a same desired relative amount, by increasing and decreasing the configuration intensity parameter by the desired relative amount.

Preferably any number of LEDs in the illumination array, less than or equal to the total number of LEDs in the illumination array, having any relative spatial configuration and associated output intensities, defines an illumination configuration.

Preferably, the LED control system has means for storing defined illumination configurations in a memory and retrieving them from the memory.

Preferably, defined illumination configurations can be stored in memory in association with particular articles for which the defined illumination configurations have been developed. When such a particular article is to be inspected, preferably, its identity, and its orientation in the focal volume are determined. The appropriate associated illumination configurations are then preferably recalled from memory and aligned with the orientation of the particular article to illuminate the particular article.

Preferably, the LED control system can be programmed to move a defined illumination configuration along a predetermined sequence of positions. Preferably, the predetermined sequence of positions can be stored in memory together with the defined illumination configuration. A particular article can then be automatically illuminated from the predetermined sequence positions by the defined illumination configuration by recalling the predetermined sequence of positions from memory together with the defined illumination configuration.

Preferably, the LED control system can illuminate an article placed in the focal volume simultaneously with a multiplicity of illumination configurations, wherein the positions of the configuration origins and configuration coordinate axes of each illumination configuration can be independently controlled.

The LED control system controls the LEDs preferably using a table of LED addresses, where each LED address corresponds to a position of a particular LED in the illumination array. An illumination configuration is therefore preferably defined by a particular set of LED addresses, or relative LED addresses, where each LED address is assigned a particular light output intensity. An illumination configuration is moved by appropriate permutation and manipulation of the illumination configuration LED addresses. Preferably, the LED addresses are integer addresses and an illumination configuration is moved by changing the addresses in an illumination configuration by the addition or subtraction of appropriate integers to the LED addresses of the illumination configuration.

There is therefore provided in accordance with a preferred embodiment of this invention an apparatus for illuminating an article placed in an inspection volume, the apparatus comprising: a plurality of light sources which produce beams of light, each of which illuminates at least a same central inspection point in the inspection volume; and a light source control system which controls the intensity with which the light sources radiate light, and wherein the light source control system controls the intensity of light emitted by any one of the plurality of light sources independently of the intensity of light emitted by any of the other of the plurality of light sources.

Preferably the light source control system controls light sources in accordance with an illumination configuration, wherein an illumination configuration comprises a configuration origin and direction, measured from convenient coordinate axes, which origin and direction define the position of the illumination configuration, and a set of light sources having a particular spatial distribution with respect to the configuration origin and direction, and wherein each light source is assigned a particular output intensity.

Preferably the illumination configuration comprises an intensity parameter which can be increased and decreased to simultaneously increase or decrease the assigned output intensities of each of the light sources by the same relative amount as the intensity parameter is increased or decreased.

Alternatively or additionally the light source control system preferably controls said light source in accordance with a trajectory for an illumination configuration, wherein a trajectory is an ordered sequence of at least two positions for the illumination configuration and a dwell time for each of the positions. Preferably, the light source control system activates the light sources, responsive to the illumination configuration, sequentially for each of the positions in the sequence, for a period of time equal to the dwell time of the position.

Alternatively or additionally the light source control system preferably comprises a memory wherein preferably, illumination configurations and trajectories can be stored in and retrieved from memory. Preferably, the light source control system activates the light sources responsive to retrieved illumination configurations and trajectories.

Alternatively or additionally, the apparatus preferably comprises a user interface, which receives control inputs and wherein the light source control system controls the light sources responsive to the control inputs.

The light sources, alternatively or additionally, are preferably located along a plurality of planar circular light rings, wherein the planes of all the light rings are parallel and wherein a line through the center of one of the light rings, perpendicular to the plane of the light ring, passes through the centers of all the light rings.

There is further provided an apparatus for illuminating an article placed in an inspection volume, the apparatus comprising: a plurality of light sources which produce beams of light, each of which illuminates at least a same central inspection point in the inspection volume, wherein the light sources are located along a plurality of planar circular light rings, wherein the planes of all the light rings are parallel and wherein a line through the center of one of the light rings, perpendicular to the plane of the light ring passes through the centers of all the light rings; and a light source control system which controls the intensity with which the light sources radiate light.

In some preferred embodiments of the present invention the arc length between any two adjacent light sources on a same light ring of the plurality of light rings is the same. The number of light sources in each light ring of the plurality of light rings is preferably a multiple of a same integer N wherein N is greater than 1. N is preferably a multiple of 12.

The arc length between adjacent light sources on one of the plurality of rings is preferably equal to the arc length between adjacent light sources on at least one other of the plurality of rings. Alternatively or additionally, the number of light rings is preferably, at least five. Preferably, the number of light sources per light ring on five of the at least five light rings are respectively 72, 60, 48, 36, and 24.

In some preferred embodiments of the present invention the apparatus comprises a planar circular light ring of white light sources.

In some preferred embodiments of the present invention, the light sources of the apparatus are mounted in a mounting configuration in the shape of a surface of revolution having an axis of revolution.

There is also provided an apparatus for illuminating an article placed in an inspection volume, the apparatus comprising: a plurality of light sources which produce beams of light, each of which illuminates at least a same central inspection point in the inspection volume, wherein the light sources are mounted in a mounting configuration in the shape of a surface of revolution having an axis of revolution; and a light source control system which controls the intensity with which the light sources radiate light.

In some preferred embodiments of the present invention, the surface of revolution has a radius of revolution which varies along the axis of revolution. The surface of revolution is preferably formed from an arc of a circle rotated about an axis of rotation that passes through an end of the arc and the center of the circle. Preferably, the surface of revolution is a hemisphere. Alternatively, the surface of revolution is preferably elliptical. Alternatively, the surface of revolution is preferably conical.

In some preferred embodiments of the present invention, alternatively or additionally, the light sources are located so that the density of light sources per unit solid angle subtended from a point in the inspection volume along a line from the point to a light source of the plurality of light sources is substantially independent of the position of the light source.

There is further provided an apparatus for illuminating an article placed in an inspection volume, the apparatus comprising: a plurality of light sources which produce beams of light, each of which illuminates at least a same central inspection point in the inspection volume, wherein the light sources are located so that the density of light sources per unit solid angle subtended from a point in the inspection volume along a line from the point to a light source of the plurality of light sources is substantially independent of the position of the light source; and a light source control system which controls the intensity with which the light sources radiate light.

In some preferred embodiments of the present invention the light sources comprise LEDs. Preferably, the LEDs radiate substantially monochromatic light.

In some preferred embodiments of the present invention the light sources comprise white light sources that radiate substantially white light.

Some preferred embodiments of the present invention comprise a non-tactile distance measuring device, that measures the distance to selected points on an article to be illuminated.

In some preferred embodiments of the present invention a light diffusing filter shadows at least a portion of the inspection zone. Preferably, the light diffusing filter is a surface of revolution.

There is also provided a method for illuminating an article placed in an inspection zone comprising: illuminating the article with light beams emitted by a multiplicity of adjacent light sources, wherein the light beams have a particular configuration of relative spatial orientation and light output intensities; and rotating the configuration about a central point in the inspection zone by an angle which is substantially smaller than the angular extent of the configuration. Preferably, rotating is achieved by illuminating the article with light beams from a first multiplicity of light sources and subsequently illuminating the article with light beams from a second multiplicity of light sources, wherein at least one of the light sources in the first and second multiplicities of light sources are the same. Alternatively or additionally, rotating through small angles is approximately achieved preferably by changing the relative intensities at which the light sources emit light.

There is further provided a method for visual inspection of an article in an inspection zone comprising: measuring distances from a reference point to a plurality of points on the surface of the article; illuminating the plurality of points; and focusing a lens system of an image acquisition system on the article using the measured distances. Preferably, the measured distances are used to provide a profile of the article.

In some preferred embodiments of the present invention a method for illuminating an article placed in an inspection zone comprises shadowing at least a portion of the inspection zone with a light diffusing filter. Preferably, the light diffusing filter is a surface of revolution.

BRIEF DESCRIPTION OF FIGURES

The invention will be more clearly understood by reference to the following description of preferred embodiments thereof in conjunction with the figures, wherein identical structures, elements or parts which appear in the figures are labeled with the same numeral, and in which:

Fig. 1 shows a cutaway schematic of an illumination dome comprising LEDs in accordance with a preferred embodiment of the present invention;

Fig. 2 shows a cutaway schematic of the illumination dome of Fig. 1 mounted with a camera and showing two LEDs emitting light beams which illuminate a focal volume in accordance with a preferred embodiment of the present invention;

Fig. 3 shows a cutaway schematic of the illumination dome in the previous figures with an illumination configuration formed using three closely spaced light beams in accordance with a preferred embodiment of the present invention;

Fig. 4 shows a schematic of the illumination configuration of Fig. 3 rotated around the axis of the illumination dome of Fig. 3 to four different positions, in accordance with a preferred embodiment of the present invention; and

Fig. 5 shows a schematic of an illumination system in accordance with a preferred embodiment of the present invention used to illuminate articles for inspection that are moved on a conveyor belt.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

Fig. 1 shows a cutaway schematic of an illumination dome 20 preferably comprising high intensity monochromatic LEDs 22 in accordance with a preferred embodiment of the present invention. Illumination dome 20 is preferably formed by first mounting LEDs 22 onto pieces of flexible circuit board material (not shown). The pieces are then shaped and joined to form the geometry of illumination dome 20.

Illumination dome 20 is preferably formed in the shape of a surface of revolution formed from an arc 21, of a circle having a radius R and center at a focal point 30, by rotating arc 21 through 360° about an axis of rotation 24. Illumination dome 20 has a focal plane 28, through focal point 30, perpendicular to axis of rotation 24. LEDs 22 are fixed to the surface of illumination dome 20 preferably along five LED rings 40_i, where the subscript, i, is an integer between 1 and 5, sequentially indicating LED rings 40_i in order of size from the largest to the smallest. LED rings 40_i are preferably, circles of intersection of the inside surface of illumination dome 20 with planes (not shown) perpendicular to the axis of rotation 24 of illumination dome 20 (*i.e.* perpendicular to the focal plane). LEDs 22, are preferably aligned so that they all illuminate a same focal volume of space (not shown), preferably substantially centered on focal point 30.

The position of each LED ring 40_i is defined by an elevation angle, θ_i, which is the angle between a line from focal point 30 to a point on the LED ring and the focal plane. Elevation angle θ_i is shown for LED ring 40_4, in Fig. 1 as the angle θ_4 between line 32 and focal plane 28. The elevation angle of LED ring 40_1 is preferably about 15°. The position of a

LED in a particular LED ring is given by an azimuth angle φ measured from a convenient line 34 in focal plane 28.

The number of LEDs 22 in each LED ring 40_i is preferably determined so that illumination array 20 has a 12-fold rotational symmetry. This requires that the number of LEDs 22 in a LED ring 40_i be a multiple of 12 and that the arc length between adjacent LEDs 22 on a same LED ring 40_i be the same for any two LEDs 22 on the LED ring 40_i.

Preferably, the arc lengths between any two adjacent LEDs 22 on any LED ring 40_i in illumination dome 20 are equal.. This constrains the elevation angles of LED rings 40_i. If the number of LEDs 22 in LED ring 40_i is n_i x 12 and Δ is the arc length between LEDs 22 on LED rings 40_i then $2\pi R\cos\theta_i = n_i \times 12 \times \Delta$. It follows that the elevation angle of a LED ring 40_i and the elevation angle of LED ring 40_1, the largest LED ring, satisfy the equation $\cos\theta_i = (n_i / n_1) \cos\theta_1$.

The number of LEDs in LED rings 40_1 through 40_5 are preferably 72, 60, 48, 36, and 24 respectively. This results in elevation angles 36.4°, 48.9°, 61.1° and 71.2°, for LED rings 40_2 to 40_5 respectively, for elevation angle θ_1=15°. The LEDs in each row are conveniently assigned consecutive integer addresses, 0→71, 72→131, 132→179, 180→215, and 216→239, for rows 40_1 to 40_5, respectively

In addition to monochromatic LEDs 22, illumination dome 20, preferably, comprises white light sources 36, mounted in a white light ring 38, between LED rings 40_4 and 40_5. White light ring 38 is preferably placed at the intersection of a plane perpendicular to axis 24 and the surface of illumination dome 20. White light sources 36 are preferably aligned so that they all illuminate the focal volume of space illuminated by LEDs 22.

A hole 50 is preferably formed in illumination dome 20, preferably centered along axis 24, for use as a viewing portal through which an image acquisition device, such as, preferably, a CCD camera, can acquire an image of an article placed inside illumination dome 20. Preferably, the focal volume and the field of view of the image acquisition device are substantially congruent. Preferably, an article to be illuminated for visual inspection is placed substantially inside the focal volume.

Fig. 2 shows a cutaway schematic of illumination dome 20 of Fig. 1 with a camera 52, mounted in hole 50 and two light beams, 54 and 56, illuminating a focal volume 58. Focal volume 58, which is preferably illuminated by all light beams (not shown) emitted by LEDs 22, is preferably centered on focal point 30. The field of view of camera 52, preferably, substantially coincides with focal volume 58.

In a preferred embodiment of the present invention a diffusing filter 59 surrounds focal volume 58. Preferably, diffusing filter 59 is a shell formed as a surface of revolution. Diffusing filters are especially useful when examining articles having highly reflective surfaces, such as polished surfaces. Such surfaces reflect light specularly, often preventing even light distribution over the surface of the article and causing bright spots which can "blind" an imaging system used to image the article.

Fig. 3 shows a cutaway schematic of illumination dome 20 with an illumination configuration 60. The configuration is formed using three closely spaced light beams 62, 64 and 66. Light beam 62, 64, and 66 have central light rays 68, 70 and 72 respectively. Central light rays 68, 70, and 72 which, of course end at the LEDs 22 from which they are radiated, are shown as extending outside of illumination dome 20 for clarity of visualization and convenience of explanation. Light beams 62, 64, and 66 are emitted by LEDs 22 at integer LED addresses 153, 154, and 155 respectively. Illumination configuration 60 is preferably defined by the set of 3 pairs of numbers (153,I_A), (154,I_B) and (155,I_C) where I_A, I_B and I_C are the light output intensities of LEDs 22 at LED addresses153, 154, and 155 respectively (i.e. light beams 62, 64 and 66 respectively).

Illumination configuration 60 can be moved to a different position in illumination dome 20 by adding or subtracting integers from each of the addresses defining illumination configuration 60 and having a LED control system (not shown) set the LEDs 22 at the rotated addresses to radiate at the appropriate output intensities. For example, to rotate illumination configuration 60 clockwise about axis 24 by 60^o, 8 is subtracted from each LED address, so that illumination configuration 60 at the rotated position is (145,I_A), (146,I_B) and (147,I_C). To rotate it back from this position by 7.5 degrees, counterclockwise around axis 24, 1 is added to the addresses and configuration 60 becomes (146, I_A), (147,I_B) and (148,I_C). It should be noted that two of the addresses in both the last positions of illumination configuration 60 are the same, though same address in both cases are paired with different output intensities.

For small angle rotations about axis 24, another way to rotate illumination configuration 60 is to adjust the beam intensities. For example if for illumination configuration

60 defined by (153,I_A), (154,I_B) and (155,I_C) $I_A>I_B>I_C$ the configuration will appear to come from an azimuth angle tilted towards LED 22 at address 153 which emits light beam 62, while if $I_A<I_B<I_C$ the configuration will appear to come from an azimuth angle tilted towards the LED 22 at address 155 which emits beam 66.

For an illumination dome having a rotational N-fold symmetry in accordance with a preferred embodiment of the present invention, any illumination configuration can be rotated about the axis of rotation to a new position and reproduced exactly at the new position if the angle of rotation between the two positions is an integer multiple of $360^{o}/N$. If it is desired to rotate an illumination configuration about the axis of rotation from a first position to a second position, where the rotation angle between the two positions is not equal to an integer multiple of $360^{o}/N$, an exact reproduction of the illumination configuration cannot generally be reproduced at the second position. However, a close approximation to the illumination configuration is generally possible at the second position by varying the relative intnsities of the sources in the illumination configuration, and the approximation is used at the second position in place of an exact reproduction.

For illumination configurations where all the LED addresses are confined to a same LED ring (*i.e.* a same elevation angle), the illumination configuration can be duplicated exactly for rotations about the axis of rotation for angles that are integer multiples of $360^{o}/n$, where n is the number of LEDs in the LED ring.

The ability to control the direction of illumination configurations with a high degree of resolution is important for adjusting illumination to compensate for randomization in the orientation of articles inspected. It is also important for examining articles having various degrees of rotational symmetry.

For example in a case of an article having an n-fold rotational symmetry about an axis, it might be desirable to first align an illumination configuration with a particular direction of the symmetry of the article and then step rotate the illumination configuration around the axis of symmetry by angles of $360^{o}/n$. The first alignment along a particular direction of symmetry might require aligning the illumination configuration direction by fine tuning beam intensities. Step rotating the illumination configuration by angles of $360^{o}/n$ around the article would then be accomplished by using different groups of LEDs, where the different groups of LEDs are rotated from each other by $360^{o}/n$.

Fig. 4 shows a schematic of illumination configuration 60 at four different positions 74, 76, 78, and 80 separated by azimuth angles of 60°, as illumination configuration 60 is rotated around axis 24 at constant elevation angle, in accordance with a preferred embodiment of the present invention. Central light ray 70 of light beam 64 in illumination configuration 60 is shown extended beyond illumination dome 20 to aid in visualizing the four positions of illumination configuration 60.

An illumination system, in accordance with a preferred embodiment of the present invention, preferably comprises an image acquisition device used to acquire images of an article illuminated by the illumination system, such as preferably a CCD camera. Focusing the CCD camera on the article is generally done by an iterative trial and error procedure which is slow. In an illumination system in accordance with a preferred embodiment of the present invention, a laser range finder is used to focus the CCD camera. Preferably, the position of the laser range finder with respect to the focal plane and optical axis of the CCD camerais accurately known. Preferably, the laser range finder measures distances to points of interest on the article at accurately known directions of the laser beam of the laser range finder. Using methods well known in the art, the laser measurements are preferably used to calculate the distances of the points of interest from the focal plane. Preferably, these distances are input to a controller of a lens system of the CCD camera which focuses the lens system on the points of interest of the article according to the distances.

In an illumination system using a laser range finder in accordance with a preferred embodiment of the present invention, the CCD camera of the illumination system can be quickly and accurately focused on specific parts of an article illuminated in a focal volume of the illumination system. It also enables focusing the CCD camera on points of interest on the article which are at different distances from the focal plane of the CCD camera while the article is in and moves through the focal volume.

A sufficient number of laser distance measurements to points of interest on the article are preferably acquired so that a distance profile of the distance of points of interest on the article to the CCD camera can be calculated. The distance profile is preferable input to the CCD camera controller which uses it to automatically, sequentially focus the lens system of the CCD camera on points of interest on the article while the article is in or passing through the focal volume.

The laser distance measurements, and especially the distance profile acquired in accordance with a preferred embodiment of the present invention can also preferably be used, employing method known in the art, to determine the orientation of the article and assess characteristics of the article for quality control.

Fig 5 shows an illumination system 90 in accordance with a preferred embodiment of the present invention used to illuminate articles 92 for inspection that are being moved on a conveyor belt 94. Illumination dome 20 (shown cutaway) is preferably mounted over conveyor belt 94 so that focal volume 58 of illumination dome 20 is substantially centered over a center line 98 of conveyor belt 94. Illumination configuration 60 preferably illuminates an article 92 when the article 92 is substantially located in focal volume 58. Light sources 22 of illumination dome 20 are preferably connected over control and data channel 100 to a processor 102.

Preferably, camera 52 is used to visualize objects 92 as they move through focal volume 58. Camera 52 is preferably connected to processor 102 by control and data channel 104. Preferably, an imaging device 106, such as a laser range finder, 3D imager or CCD camera is mounted over conveyor belt 94 and scans objects 92 before they reach illumination dome 20. Imaging device 106, preferably measures the distance to a plurality of points on each of articles 92 as they pass by imaging device 106. Preferably, imaging device 106 is connected by control and data channel 108 to processor 102. Preferably imaging device 106 transmits the distance measurements to processor 102 over channel 108. Preferably, imaging device 106 also transmits data to processor 102 which processor 102 uses to determine the orientation of each of articles 92 with respect to illumination dome 20 Preferably, processor 102 uses the distance data to focus camera 52 on a plurality of points on each of articles 92 when the article 92 is substantially located in focal volume 58. Preferably, processor 102 uses the determined orientation of an article 92 with respect to illumination dome 20 to control the direction and intensity of illumination configuration 60.

Processor 102 is preferably connected to a video display 110, and a user interface such as a keyboard 112. Video display 110 preferably displays the illumination state of each of light sources 22. Preferably, video display 110 also shows the article 92 which is present in focal volume 58 and the pattern of light with which the article 92 is illuminated. Preferably, a user can input instructions to processor 102 through interface 112 that causes processor 102 to adjust the direction and intensity of illumination configuration 60. Preferably, the user, using interface 112, can instruct processor 102 to retrieve from a memory different appropriate defined illumination configurations with which to illuminate articles 92 in focal volume 58.

The present invention has been described using a non limiting detailed description of a preferred embodiment thereof. Variations of the embodiment described will occur to persons of the art. For example, illumination domes can be formed from ellipses of revolution instead of circles of revolution, and light sources can be distributed in two illumination configurations which are mirror images of each other with respect to a plane through a focal volume. There are also different formats and coordinate systems that can be used to define the positions of LEDs in an illumination array and to define and move illumination configurations and these will occur to persons of the art.

The detailed description is provided by way of example and is not meant to limit the scope of the invention which is limited only by the following claims:

CLAIMS

1. Apparatus for illuminating an article placed in an inspection volume, the apparatus comprising:

a plurality of light sources which produce beams of light, each of which illuminates at least a same central inspection point in the inspection volume; and

a light source control system which controls the intensity with which the light sources radiate light, and

wherein the light source control system controls the intensity of light emitted by any one of the plurality of light sources independently of the intensity of light emitted by any of the other of the plurality of light sources.

2. Apparatus according to claim 1 wherein said light source control system controls light sources in accordance with an illumination configuration, wherein an illumination configuration comprises a configuration origin and direction, measured from convenient coordinate axes, which origin and direction define the position of the illumination configuration, and a set of light sources having a particular spatial distribution with respect to the configuration origin and direction, wherein each light source is assigned a particular output intensity

3. Apparatus according to claim 2 wherein the illumination configuration comprises an intensity parameter which can be increased and decreased to simultaneously increase or decrease the assigned output intensities of each of the light sources by the same relative amount as the intensity parameter is increased or decreased.

4. Apparatus according to claim 2 or claim 3 wherein said light source control system controls said light source in accordance with a trajectory for an illumination configuration, wherein a trajectory is an ordered sequence of at least two positions for the illumination configuration and a dwell time for each of the positions.

5. Apparatus according to claim 4 wherein the light source control system activates the light sources, responsive to the illumination configuration, sequentially for each of the positions in the sequence, for a period of time equal to the dwell time of the position.

6. Apparatus according to any of claims 2 - 5 wherein the light source control system comprises a memory.

7. Apparatus according to claim 6 wherein illumination configurations and trajectories can be stored in and retrieved from memory.

8. Apparatus according to claim 7 wherein the light source control system activates the light sources responsive to retrieved illumination configurations and trajectories.

9. Apparatus according to any of the preceding claims and including a user interface, which receives control inputs and wherein the light source control system controls the light sources responsive to said control inputs.

10. Apparatus according to any of the above claims wherein the light sources are located along a plurality of planar circular light rings, wherein the planes of all the light rings are parallel and wherein a line through the center of one of the light rings, perpendicular to the plane of the light ring, passes through the centers of all the light rings.

11. Apparatus for illuminating an article placed in an inspection volume, the apparatus comprising:

a plurality of light sources which produce beams of light, each of which illuminates at least a same central inspection point in the inspection volume, wherein the light sources are located along a plurality of planar circular light rings, wherein the planes of all the light rings are parallel and wherein a line through the center of one of the light rings, perpendicular to the plane of the light ring passes through the centers of all the light rings; and

a light source control system which controls the intensity with which the light sources radiate light.

12. Apparatus according to claim 10 or claim 11 wherein the arc length between any two adjacent light sources on a same light ring of the plurality of light rings is the same.

13. Apparatus according to claim 12 wherein the number of light sources in each light ring of the plurality of light rings is a multiple of a same integer N wherein N is greater than 1.

14. Apparatus according to claim 13 wherein N is a multiple of 12.

15. Apparatus according to any of claims 12 - 14 wherein the arc length between adjacent light sources on one of the plurality of rings is equal to the arc length between adjacent light sources on at least one other of the plurality of rings.

16. Apparatus according to any of claims 12-15 wherein the number of light rings is at least five.

17. Apparatus according to claim 16 wherein the number of light sources per light ring on five of the at least five light rings are respectively 72, 60, 48, 36, and 24.

18. Apparatus according to any of claims 10 - 17 and including a planar circular light ring of white light sources.

19. Apparatus according to any of claims 11 - 18 wherein the light sources are mounted in a mounting configuration in the shape of a surface of revolution having an axis of revolution.

20. Apparatus for illuminating an article placed in an inspection volume, the apparatus comprising:

a plurality of light sources which produce beams of light, each of which illuminates at least a same central inspection point in the inspection volume, wherein the light sources are mounted in a mounting configuration in the shape of a surface of revolution having an axis of revolution; and

a light source control system which controls the intensity with which the light sources radiate light.

21. Apparatus according to claim 19 or claim 20, wherein the surface of revolution has a radius of revolution which varies along the axis of revolution.

22 Apparatus according to claim 21 wherein the surface of revolution is formed from an arc of a circle rotated about an axis of rotation that passes through an end of the arc and the center of the circle.

23. Apparatus according to any of claim 22 wherein the surface of revolution is a hemisphere.

24. Apparatus according to any of claim 21 wherein the surface of revolution is elliptical.

25. Apparatus according to any of claim 21 wherein the surface of revolution is conical.

26. Apparatus according to any of the preceding claims wherein the light sources are located so that the density of light sources per unit solid angle subtended from a point in the inspection volume along a line from the point to a light source of the plurality of light sources is substantially independent of the position of the light source.

27. Apparatus for illuminating an article placed in an inspection volume, the apparatus comprising:

a plurality of light sources which produce beams of light, each of which illuminates at least a same central inspection point in the inspection volume, wherein the light sources are located so that the density of light sources per unit solid angle subtended from a point in the inspection volume along a line from the point to a light source of the plurality of light sources is substantially independent of the position of the light source; and

a light source control system which controls the intensity with which the light sources radiate light.

28. Apparatus according to any of the previous claims wherein the light sources comprise LEDs.

29. Apparatus according to claim 28 wherein the LEDs radiate substantially monochromatic light.

30. Apparatus according to any of the previous claims wherein the light sources comprise white light sources that radiate substantially white light.

31. Apparatus according to any of the preceding claims comprising a non-tactile distance measuring device, that measures the distance to selected points on an article to be illuminated.

32. A method for illuminating an article placed in an inspection zone comprising:

illuminating the article with light beams emitted by a multiplicity of adjacent light sources, wherein the light beams have a particular configuration of relative spatial orientation and light output intensities; and

rotating the configuration about a central point in the inspection zone by an angle which is substantially smaller than the angular extent of the configuration.

33. A method according to claim 32 wherein rotating is achieved by illuminating the article with light beams from a first multiplicity of light sources and subsequently illuminating the article with light beams from a second multiplicity of light sources, wherein at least one of the light sources in the first and second multiplicities of light sources are the same.

34. A method according to claim 32 wherein rotating through small angles is approximately achieved by changing the relative intensities at which the light sources emit light.

35. A method for visual inspection of an article in an inspection zone comprising:

measuring distances from a reference point to a plurality of points on the surface of the article;

illuminating the plurality of points; and

focusing a lens system of an image acquisition system on the article using the measured distances.

36. A method according to claim 35 wherein the measured distances are used to provide a profile of the article.

37. Apparatus according to any of claims 1 - 31 wherein a light diffusing filter shadows at least a portion of the inspection zone.

38. Apparatus according to claim 37 wherein the light diffusing filter is a surface of revolution.

39. A method according to any of claims 32 - 36 comprising shadowing at least a portion of the inspection zone with a light diffusing filter.

40. A method according to claim 39 wherein the light diffusing filter is a surface of revolution.

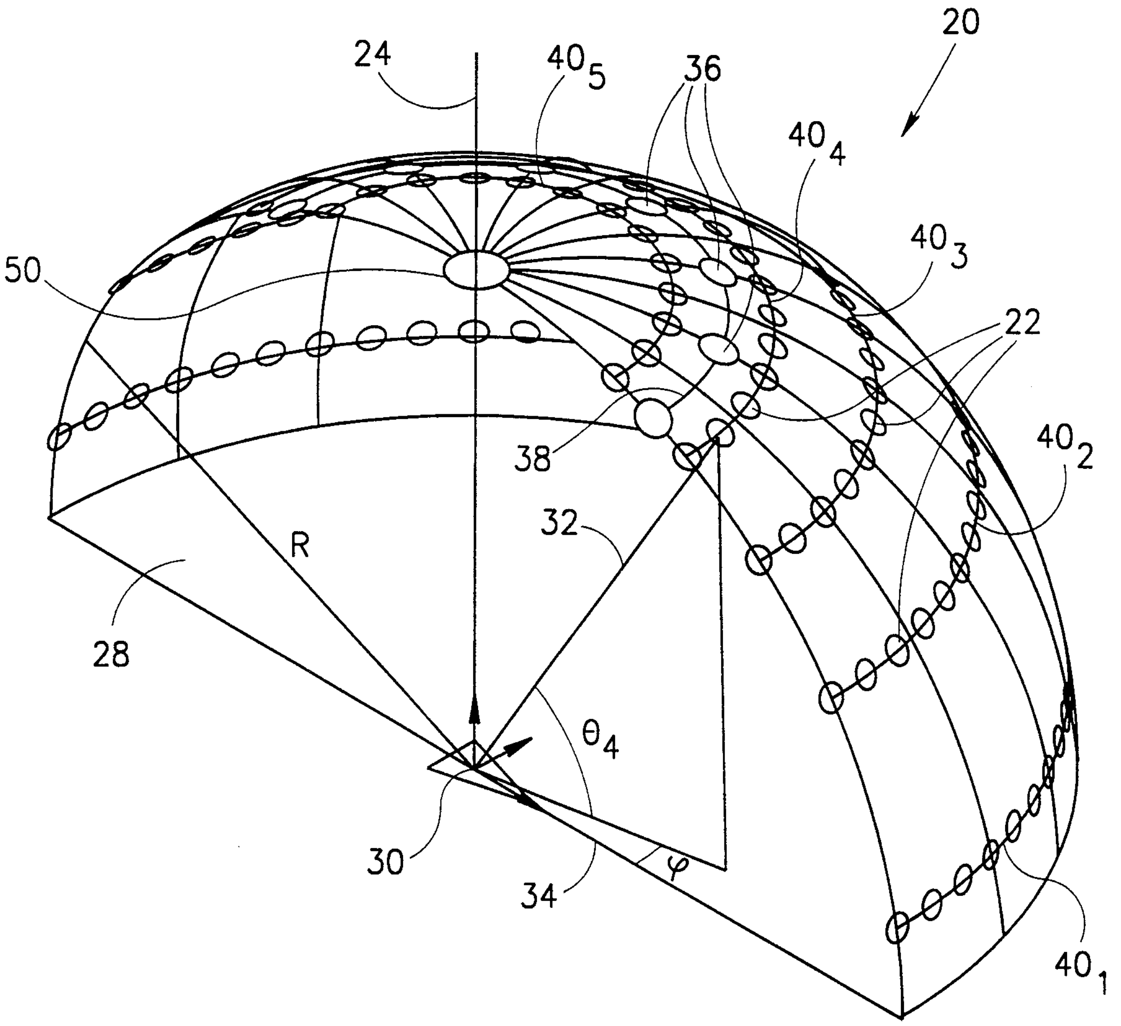

FIG.1

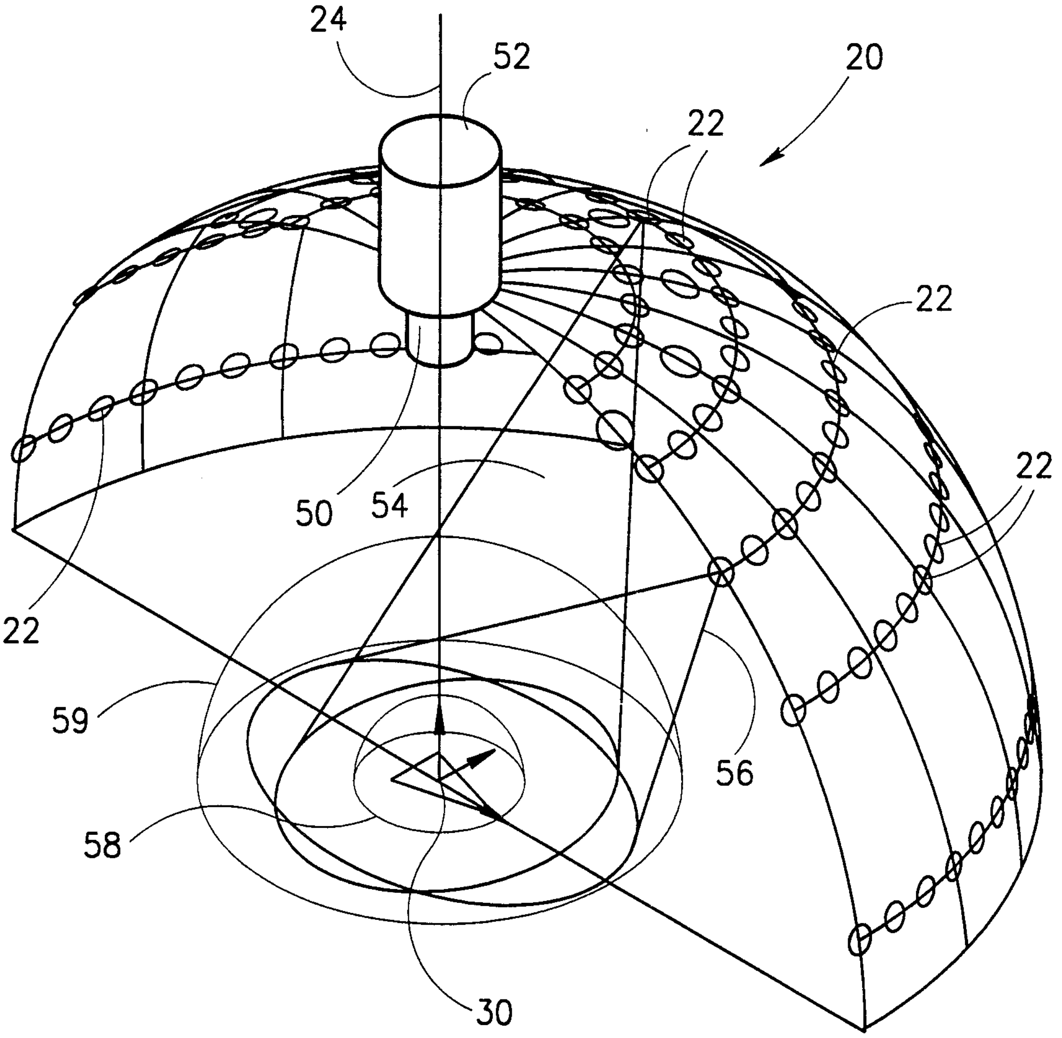

FIG.2

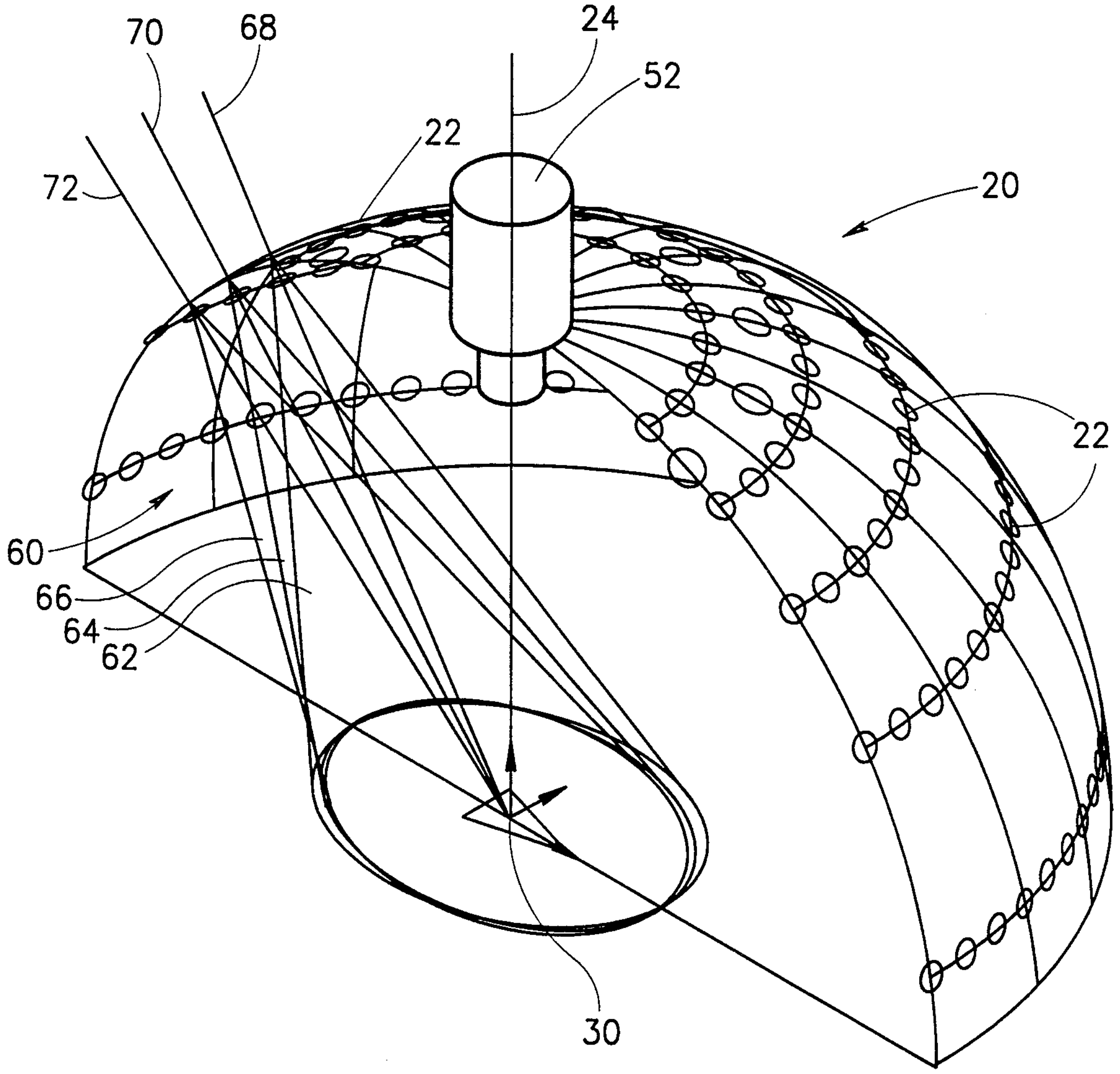

FIG.3

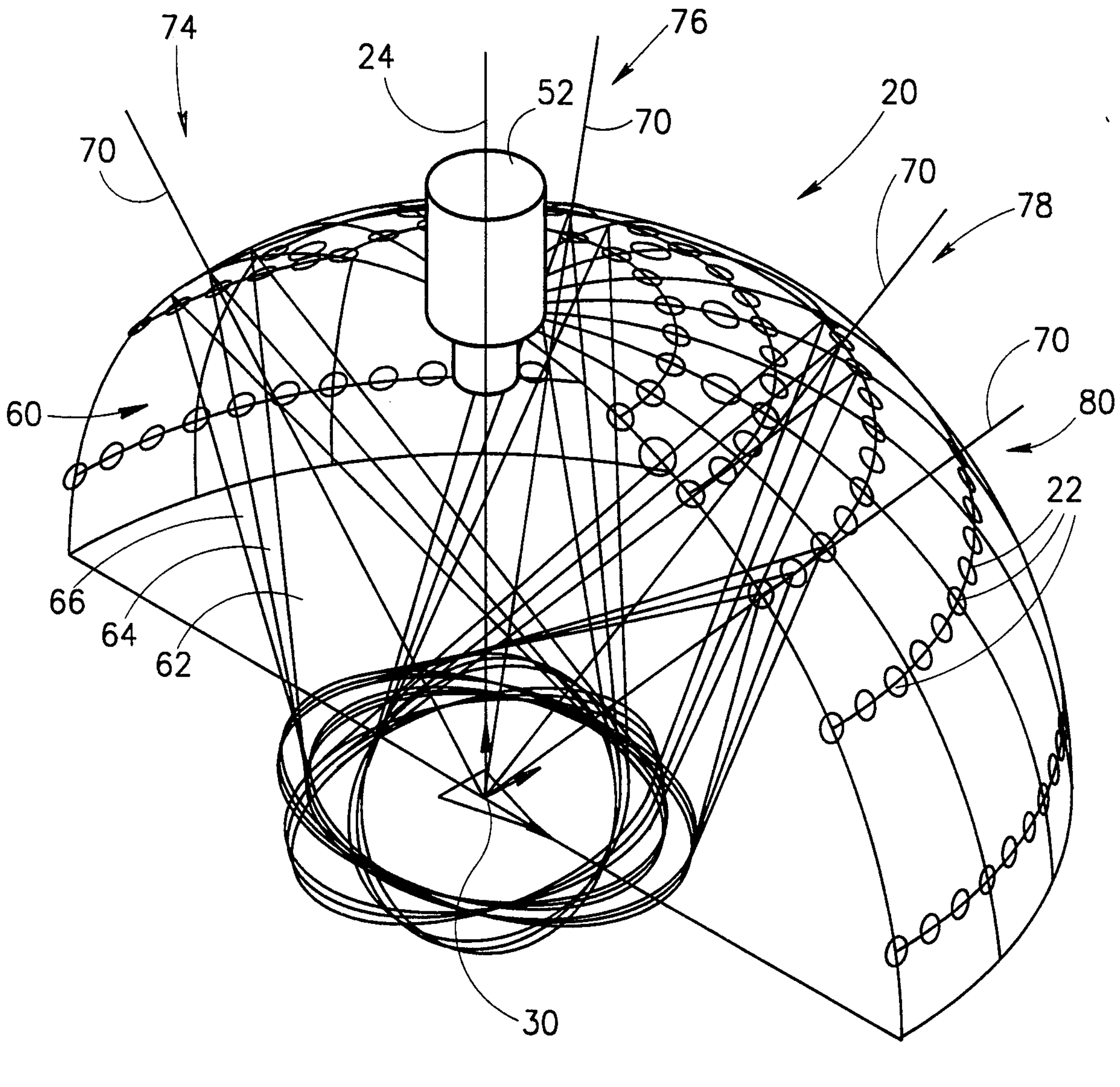

FIG.4

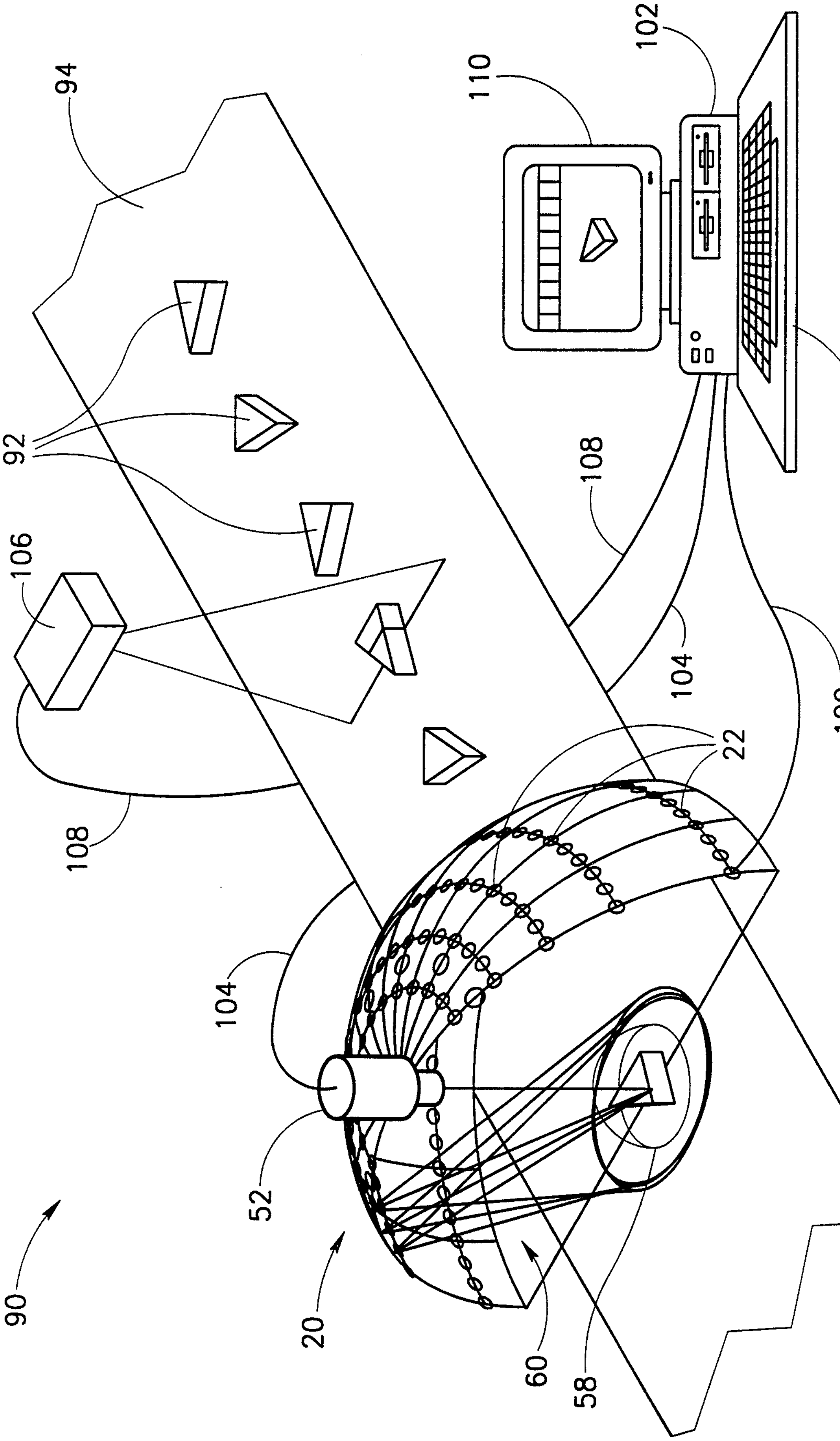

FIG.5

INTERNATIONAL SEARCH REPORT

Intern ial Application No
PCT/IL 97/00350

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 G01N21/88

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6 G01N

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	DE 41 23 916 A (MALZ REINHARD) 23 January 1992	1-12,16, 19,20, 22,23, 28-30, 32,33
	see page 2, line 67 - page 3, line 25 see page 4, line 10 - line 48; claim 1; figures 1,2 ---	
X	US 4 882 498 A (COCHRAN DON W ET AL) 21 November 1989	1,9, 20-24, 28-30
A	see column 3, line 1 - column 7, line 19; figures 1,3,4 ---	11
X	WO 91 06846 A (PRESSCO INC) 16 May 1991 see page 4, line 28 - page 5, line 25; figure 1 ---	1,9
	-/--	

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

[X] Patent family members are listed in annex.

° Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

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

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

"&" document member of the same patent family

1

Date of the actual completion of the international search	Date of mailing of the international search report
17 June 1998	12.08.98

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	Tabellion, M

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INTERNATIONAL SEARCH REPORT

Interr ıal Application No
PCT/IL 97/00350

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 4 893 223 A (ARNOLD AARON L) 9 January 1990 see abstract; figures 3,4	1,11,20
A	US 5 369 492 A (SUGAWARA K) 29 November 1994 see column 6, line 32 - line 39	1
A	EP 0 356 680 A (SIEMENS AG) 7 March 1990 see claims 1-5; figures 1,2	1
A	EP 0 662 609 A (APPLIED INTELLIGENT SYSTEMS INC) 12 July 1995 & US 5 519 496 A (BORGERT G ET AL) 21 May 1996 cited in the application	

1

INTERNATIONAL SEARCH REPORT

International application No.
PCT/IL 97/00350

Box I Observations where certain claims were found unsearchable (Continuation of item 1 of first sheet)

This International Search Report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:

2. ☐ Claims Nos.:
because they relate to parts of the International Application that do not comply with the prescribed requirements to such an extent that no meaningful International Search can be carried out, specifically:

3. ☐ Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box II Observations where unity of invention is lacking (Continuation of item 2 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

see additional sheet

1. ☐ As all required additional search fees were timely paid by the applicant, this International Search Report covers all searchable claims.

2. ☐ As all searchable claims could be searched without effort justifying an additional fee, this Authority did not invite payment of any additional fee.

3. ☐ As only some of the required additional search fees were timely paid by the applicant, this International Search Report covers only those claims for which fees were paid, specifically claims Nos.:

4. ☒ No required additional search fees were timely paid by the applicant. Consequently, this International Search Report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

1-34, 37-40

Remark on Protest

☐ The additional search fees were accompanied by the applicant's protest.

☐ No protest accompanied the payment of additional search fees.

FURTHER INFORMATION CONTINUED FROM PCT/ISA/ 210

1. Claims: 1-34; 37-40 insofar as dependent on 1-34

   Apparatus and method for illuminating an article

2. Claims: 35,36; 37-40 insofar as dependent on 35,36

   Auto focus for image acquisition system

INTERNATIONAL SEARCH REPORT

Information on patent family members

International Application No
PCT/IL 97/00350

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
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INTERNATIONAL SEARCH REPORT

Information on patent family members

Interna l Application No
PCT/IL 97/00350

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
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Form PCT/ISA/210 (patent family annex) (July 1992)