(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
19 December 2002 (19.12.2002)

PCT

(10) International Publication Number
WO 02/101645 A2

(51) International Patent Classification[7]: **G06T**

(21) International Application Number: PCT/US02/18321

(22) International Filing Date: 10 June 2002 (10.06.2002)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
60/297,081 8 June 2001 (08.06.2001) US

(71) Applicant: **UNIVERSITY OF SOUTHERN CALIFORNIA** [US/US]; Office of Technology Licensing, 3716 South Hope Street, Suite 313, Los Angeles, CA 90007-4344 (US).

(72) Inventors: **DEBEVEC, Paul, E.**; 4105 Pacific Avenue #3, Marina del Rey, CA 90292 (US). **WAESE, Jamie**; 960-D 19th Street, Santa Monica, CA 90403 (US).

(74) Agents: **BROWN, Marc, E.** et al.; McDermott, Will & Emery, 2049 Century Park East, Suite 3400, Los Angeles, CA 90067 (US).

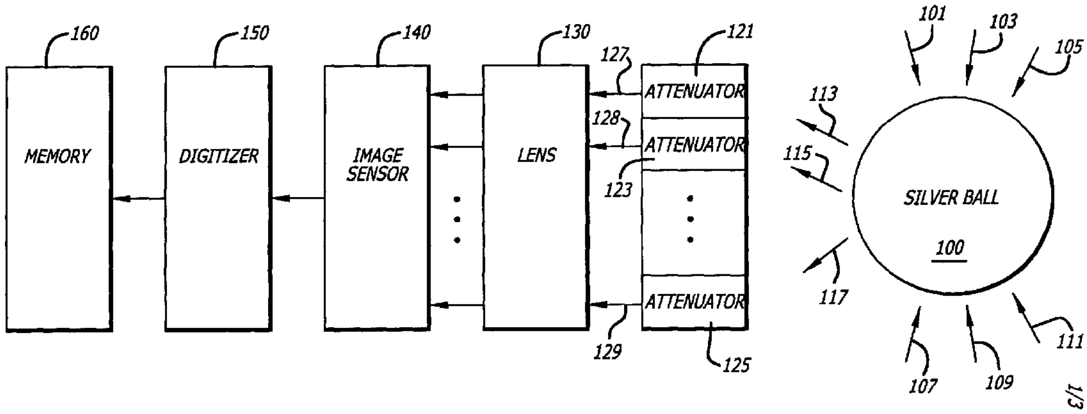
(81) Designated States *(national)*: AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DZ, EC, EE, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, MZ, NO, NZ, OM, PH, PL, PT, RO, RU, SD, SE, SG, SI, SK, SL, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VN, YU, ZA, ZM, ZW.

(84) Designated States *(regional)*: ARIPO patent (GH, GM, KE, LS, MW, MZ, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE, TR), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Published:
— *without international search report and to be republished upon receipt of that report*

For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

(54) Title: REAL TIME HIGH DYNAMIC RANGE LIGHT PROBE



(57) Abstract: A real time high dynamic range light probe. One emQodiment advantageously includes a curved, reflective surface for creating a reflected image of the desired image; a plurality of image attenuators, each positioned to receive the reflected image and to create an attenuated image of the reflected image at an attenuation level that is different from the attenuation level of the other images; and an image capturing apparatus positioned to receive and simultaneously capture all of the attenuated images.

WO 02/101645 A2

REAL TIME HIGH DYNAMIC RANGE LIGHT PROBE

BACKGROUND OF THE INVENTION

[0001] 1. Field of Invention

[0002] This invention relates to image capturing systems and methods. More particularly, this invention relates to computer graphic techniques for compositing elements into live action scenes.

[0003] 2. Description of Related Art

[0004] To successfully composite computer graphic elements into live action scenes, the lighting of the computer graphic object preferably should match the lighting of the scene into which it is being composited.

[0005] The dynamic range of the scene is often greater than the dynamic range of the image capturing device, be it photographic film or an electronic image sensor. As a consequence, important differences between the intensities at very low levels of light and very high levels of light are lost. All of the different low levels of light are often captured as black, while all of the different high levels of light are often captured as white.

[0006] One effort at overcoming this problem has been to sequentially take a set of photographs of the image of the desired scene, each at a progressively increasing (or decreasing) exposure level. Each photograph captures differences in the intensity levels of the light within a particular range of the full dynamic range of intensity levels. The photograph taken with the least exposure, for example, best captures differences among the high intensities, while the photograph taken with the greatest exposure best captures the differences at the low intensities. The information in all of the photographs is then combined into a single high dynamic range image using appropriate computational techniques.

[0007] Unfortunately, this approach is cumbersome, time-consuming and often yields less-than-fully-accurate results. It is also difficult to adapt to the recordation of rapidly-moving images or to the recordation of rapid movement of the image capturing apparatus within a still environment.

SUMMARY OF THE INVENTION

[0008] One object of the invention is to obviate these as well as other problems in the prior art.

[0009] Another object of the invention is to provide a high dynamic range light probe that is not cumbersome.

[0010] Another object of the invention is to provide a high dynamic range light probe that is easy to use.

[0011] Another object of the invention is to provide a high dynamic range light probe that is accurate.

[0012] A still further object of the invention is to provide a high dynamic range light probe that operates in real time, making it easy to record quickly moving images or quick movement of the light probe within a still environment.

[0013] A still further object of the invention is to provide an image capturing apparatus and method that captures the high dynamic range of the image.

[0014] A still further object of the invention is to provide an image capturing apparatus and method that captures the high dynamic range of a moving image.

[0015] A still further object of the invention is to provide an image capturing apparatus and method that captures the high dynamic range when the capturing apparatus is moving.

[0016] These as well as still further features, objects and benefits of the invention are achieved with a method and apparatus that includes a curved reflective surface for creating a reflected image of the desired image, a plurality of image attenuators, each positioned to receive the reflected image and to create an attenuated image of the reflected image at an attenuation level that is different from the attenuation level of the other image attenuators, and an image capturing apparatus positioned to receive and simultaneously capture all of the attenuated images.

[0017] In a further embodiment, the image capturing apparatus includes an image sensor for capturing the attenuated images and for producing an electronic signal representative of them, a digitizer for digitizing the electronic signal and a memory for storing the digitized signal.

[0018] In a further embodiment, a lens is in communication with the reflected image for focusing the reflected image and for generating a focused image of the reflected image.

[0019] In a further embodiment, a splitter is positioned to receive the focused image from the lens and splits the focused image into a plurality of split images, each split image being directed to one of the image attenuators.

[0020] In a still further embodiment, the image capturing apparatus includes a plurality of image sensors, each positioned to capture the attenuated image from an image attenuator and to generate an electronic signal representative of the image cast upon it. A digitizer digitizes the electronic signals and a memory stores the digitized signals.

[0021] In a still further embodiment, the attenuated images are combined by an image combining system, either before or after they are stored in the memory.

[0022] In a still further embodiment, the curved reflective surface includes a silver ball.

[0023] In a still further embodiment, the desired image changes as a function of time and the image capturing apparatus captures the desired image at different points in time.

[0024] In a still further embodiment, the image is directly captured without any intervening reflective surface.

[0025] In a still further embodiment, the attenuation level of one of the image attenuators is zero thus causing no attenuation.

[0026] In a still further embodiment, an image attenuator includes a light filter. In another embodiment, an image attenuator includes a light-blocking aperture controlled by a shutter.

[0027] In a still further embodiment, the image capturing apparatus includes photographic film and all of the attenuated images are directed onto the photographic film.

[0028] These as well as still further objects, features and benefits of the invention will now become clear upon an examination below of the Detailed

Description of Illustrative Embodiments of the Invention, in conjunction with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

[0029] FIG. 1 illustrates one embodiment of the invention using attenuators positioned in front of the lens and a single image sensor.

[0030] FIG. 2 illustrates a set of captured images produced by the embodiment of the invention shown in Fig. 1.

[0031] FIG. 3 illustrates the physical layout of certain components in one embodiment of the invention.

[0032] FIG. 4 illustrates more details about one embodiment of the attenuators.

[0033] FIG. 5 illustrates another embodiment of the invention using a beam splitter, attenuators positioned after the lens and a single image sensor.

[0034] FIG. 6 illustrates another embodiment of the invention using a plurality of image sensors.

[0035] FIG. 7(a)-(c) illustrates another embodiment of the image attenuators.

[0036] FIG. 8 illustrates an image combining system that can advantageously be used to combine the multiple images produced by the invention.

DETAILED DESCRIPTION OF ILLUSTRATIVE EMBODIMENTS OF INVENTION

[0037] FIG. 1 illustrates one embodiment of the invention using attenuators positioned in front of the lens and a single image sensor.

[0038] As shown in FIG. 1, a silver ball reflects images of light impinging upon the silver ball **100** from numerous directions, including directions **101, 103, 105, 107, 109** and **111**. In turn, the silver ball **100** produces a reflection of the images that it collects in reflections, such as reflections **113, 115 and 117**.

[0039] A light probe is, in fact, an established technique in the art for gathering a three-dimensional image substantially surrounding a single point in an environment and for causing that image to be substantially reflected in a two dimensional image. As illustrated in FIG. 1, a curved reflective surface such as a silver ball is typically used. Of course, other types of curved reflective surfaces could be used as well. The net effect of using the silver ball **100** is to allow an omni-directional picture to be taken of a surrounding environment.

[0040] The two-dimensional image that travels as reflections **113, 115, 117** reach a plurality of image attenuators, such as image attenuators **121, 123** and **125**. The image that enters each attenuator is attenuated a certain amount by the attenuator. Preferably, the attenuation amount of each of the attenuators is different, typically increasing in substantially-equal increments, with one of the attenuators providing an attenuation amount that is zero, i.e., no attenuation at all.

[0041] The attenuation amount of the attenuator with the greatest attenuation, on the other hand, is typically selected to insure that variations in very bright intensities are distinguishably captured by the image capturing device that is associated with this attenuator (as detailed more below).

[0042] The images **127, 128** and **129** that emanate, respectively, from the attenuators **121, 123 and 125** are substantially the same, except for variations caused by their slightly different perspectives and except for differences in their attenuation level. All of these images are directed through a lens **130** that focuses the images on an electronic sensor **140**.

[0043] The electronic sensor can be any type of device that converts a visual image into an electronic signal, such as a CCD. Alternatively, photographic film or any other type of image capturing device can be used in place of the electronic sensor. In each instances, the electronic sensor or other capturing device has a dynamic range that is less than the dynamic range of the image to be captured.

[0044] The output of the image sensor is digitized by a digitizer **150** in accordance with well known techniques, such as analog-to-digital conversion techniques. The output of the digitizer **150** is directed to a memory **160**, such as a flash memory, RAM, video tape, or any other type of long or short term memory. Although a digitizer is shown as being interposed between the image sensor **140** and the memory **160**, the memory could be an analog memory, thus obviating the need for the digitizer **150** at this point in the system.

[0045] FIG. 2 illustrates a set of captured images produced by the embodiment of the invention shown in FIG. 1. As shown in FIG. 2, the image sensor **140** (or photographic film) has captured the images from the lens **130** in images **203**, **205** and **207**. As previously indicated, each of the images **203**, **205** and **207** are substantially identical, except that they represent the original image at a different attenuation level and perspective.

[0046] Although being shown as being positioned in a single horizontal row, it is to be understood that the images **203**, **205**, and **207** could be in numerous other arrangements, such as in a vertical arrangement, in a plurality of rows and columns, in a circular arrangement, or in any other type of arrangement. Of course, corresponding changes in the position of the attenuators **121**, **123** and **125** would also be needed, or some other adjustment would need to be made in the paths of the images as they traveled from the light probe to the image sensor **123** (or photographic film).

[0047] FIG. 3 illustrates the physical layout of certain components of one embodiment of the invention. In this embodiment, the attenuators **121**, **123** and **125**, the lens **130** and the image sensor **140** (or photographic film) are housed in a single camera unit **301** that is affixed to an arm **305** to which the silver ball **100** is also affixed, preferably at a significant separation distance from the camera **301**. The large separation distance between the silver ball **100** and the camera **301** minimizes the differences between the perspectives of the images **203**, **205** and **207**, thus easing the processing that will later need to be done to compensate for these differences.

[0048] Although only three attenuators have thus-far been illustrated and discussed, it is of course to be understood that a different number of attenuators may also be used, such as 2, 4, 5 or 6 or any other number greater than one.

[0049] FIG. 4 illustrates more details about one embodiment of the image attenuators. In this embodiment, five image attenuators are illustrated as having been fabricated on a faceted lens **400** commonly used to create photographic kaleidoscope effects. The lens **400** is segmented into areas **401**, **403**, **405**, **407** and **409**. Areas **403**, **405**, **407** and **409** each have had successively increasing values of neutral density gel applied, effectively imitating a 3.333, 6.666, 10 and 13.33 stop. No gels has been placed on the center area **401**, thus giving it an attenuation of 0. This multi-image filter is then placed over the lens **130** of the camera **301**.

[0050] FIG. 5 illustrates another embodiment of the invention using a beam splitter, attenuators positioned after the lens and a single film or sensor. The embodiment of FIG. 5 is the same as FIG. 1 in terms of the silver ball **500** and the light that impinges upon the probe **500** from the numerous directions, including directions **501**, **503**, **505**, **507**, **509**, and **511**. A reflection **513**, however, is directed to a lens **521** directly, rather than through any attenuators. After focusing the reflection, the focused reflection **523** is directed to a beam splitter **530** which splits the reflection into a plurality of paths, such as paths **531**, **533** and **535**. Each of these paths, in turn, are directed to attenuators **541**, **543**, and **545**, respectively, which are then attenuated by the attenuators and digitized by an image sensor **551**, digitized by a digitizer **561,** and stored in a memory **571,** in the same manner and with the same variations that were discussed above in connection with FIGS. 1-3. In this embodiment, however, differences in the images **203**, **205** and **207** due to differences in perspective are substantially reduced, reducing the processing that must be done to combine the images (described below). Although referred to as a single beam splitter, it is of course to be understood that the beam splitter **530** may, in fact, comprise a plurality of beam splitters and other optical and image processing apparatus that are needed to create a split beam for each of the attenuators.

[0051] FIG. 6 illustrates another embodiment of the invention using a plurality of image sensors. As shown in FIG. 6, attenuated and focused reflections of the image **601**, **603**, and **605** are each directed to a separate image sensor, such as image sensors **611**, **613** and **615**. This embodiment is similar to the embodiment shown in Fig. 1, except that the attenuated and focused images are each captured on a separate image sensor, rather than on a single image sensor. This approach can provide better resolution in the captured image. Like in FIG. 1, including the variations of FIG. 1 that were discussed, the output from each image sensor may be digitized by a digitizer **621** and stored in a memory **631.**

[0052] FIG. 7(a)-(c) illustrate another embodiment of the image attenuators. In this embodiment, the attenuators are implemented with light-blocking apertures **701**, **703** and **705**, each having a differently-sized aperture. This embodiment is useful when the exposure of the image sensors (or photographic film) is regulated by a shutter or other mechanism. Alternatively, the attenuators can be constructed of devices that combine one or more of the features of the attenuators that have thus-far been discussed.

[0053] FIG. 8 illustrates an image combining system that can advantageously be used to combine the multiple images produced by the invention. Either before or after the image is stored in the memory of the invention, such as memory **160** in FIG. 1 or memory **631** in FIG. 6, the set of attenuated images **801**, **803** and **805** are preferably combined into a single high dynamic range image **809** by an image combining system **807**. The image combining system **807** includes hardware and/or software that typically combines the images on a pixel-by-pixel basis. The value of each pixel is equated to its value in the captured image that most accurately reflects that pixel's value. This is typically accomplished by selecting the value of the pixel from the captured image that has an attenuation level that is most closely matched to that value. For example, the value of a pixel at a very low luminance level is selected from the captured image that was created by the attenuator having the smallest attenuation value. Conversely, the value of a pixel with a very high luminance level is selected from the captured image that was created by the attenuator having the highest level of attenuation. In addition to selecting the most accurate luminance values, the combination process may also make adjustments for the slight differences in the perspectives of the images when captured in accordance with the embodiment of the invention that is shown in FIG. 1.

[0054] In the alternate embodiment, the value of each pixel in the high dynamic range image is equated to a weighted average of the value of this pixel in several of the captured images.

[0055] The techniques that were used in the prior art to combine sequential images taken at different exposure may also be used here to combine the images that are simultaneously captured. For more details concerning the combining techniques, reference is made to P.E. Debevec et al., Recovering Dynamic Range Radiance Maps from Photographics, Proceedings of SIGGRAPH 97, Computer Graphics Proceedings, Annual Conference Series, pp. 369-378 (August 1997, Los Angeles, California). Addison Wesley (edited by Turner

Whitted) (ISBN 0-89791-896-7), the contents of which are incorporated herein by reference.

[0056] The image capturing apparatus can also be used to capture images that vary as a function of time because the images are moving or because the image capturing apparatus is moving. This can be done by capturing a series of images, each at a different point in time, as the images change with time, such as is done in taking a motion picture. At each instant, of course, a set of attenuated images are captured.

[0057] The image capturing apparatus can also be used to capture images directly, without having been first reflected off of a curved surface.

[0058] In short, although various embodiments of the invention have thus-far been discussed, it is to be understood that the invention is applicable to numerous additional embodiments, being limited solely by the claims that now follow.

WE CLAIM:

1. An image capturing apparatus for capturing a desired image comprising:
    a) a curved reflective surface for creating reflections of the desired image;
    b) a plurality of image attenuators, each positioned to receive a reflection of the desired image from said curved reflective surface and to create an attenuated image therefrom at an attenuation level that is different from the attenuation level of the other image attenuators; and
    c) an image capturing device to which all of the attenuated images are directed for simultaneously capturing all of the attenuated images.
2. The image capturing apparatus of Claim 1 further including an image combining system for combining the captured images into a combined image.
3. The image capturing apparatus of Claim 2 wherein said image combining system combines each attenuated image by dividing each captured image into pixels and by basing the intensity level of each pixel in the combined image on the intensity level which that pixel has in one of the captured images.
4. The image capturing apparatus of Claim 1 further including:
    a) a lens in communication with a reflection of the desired image for generating a focused image of the reflection; and
    b) a splitter positioned to receive the focused image for splitting the focused image into a plurality of split images, each split image being directed to one of said image attenuators.
5. The image capturing apparatus of Claim 1 wherein said image capturing device includes photographic film.
6. The image capturing apparatus of Claim 1 wherein said image capturing device includes an image sensor for generating a signal representative of the image cast upon it.
7. The image capturing apparatus of Claim 1 wherein said curved reflective surface includes a silver ball.

8. The image capturing apparatus of Claim 7 wherein said silver ball is mounted on a mount.

9. The image capturing apparatus of Claim 1 wherein the desired image changes as a function of time and wherein said image capturing device captures the desired image at different points in time.

10. The image capturing apparatus of Claim 1 wherein the attenuation level of one of said image attenuators is zero.

11. The image capturing apparatus of Claim 1 wherein at least one of said image attenuators includes a light filter.

12. The image capturing apparatus of Claim 1 wherein at least one of said image attenuators includes a light-blocking aperture regulated by a shutter.

13. A method of capturing a desired image comprising:

    a) creating reflections of the desired image using a curved reflective surface;
    b) creating a plurality of attenuated images, each from a reflection at an attenuation level that is different from the attenuation level of the other attenuated images; and
    c) simultaneously capturing all of the attenuated images.

14. The method of capturing of Claim 13 further comprising combining the attenuated images into a combined image.

15. The method of capturing of Claim 14 wherein the combined image includes pixels and wherein each pixel in the combined image is based on the intensity level of that pixel has in one or more of the attenuated images.

16. The method of capturing of Claim 13 further comprising:

    a) generating a focused image of the reflection;
    b) splitting the focused image into a plurality of split images; and
    c) directing each split image to an image attenuator.

17. The method of capturing of Claim 13 wherein the attenuated images are all captured on photographic film.

18. The method of capturing of Claim 13 wherein the attenuated images are directed to one or more image sensors.

19. The method of capturing of Claim 13 wherein the desired image changes as a function of time and wherein the desired image is captured at different points in time.

20. The method of capturing of Claim 13 wherein one of the attenuation levels is zero.

21. An image capturing apparatus for capturing a desired image comprising:

   a) a plurality of image attenuators, each positioned to receive the desired image and to create an attenuated image therefrom at an attenuation level that is different from the attenuation level of the other image attenuators; and

   b) an image capturing device to which all of the attenuated images are directed for simultaneously capturing all of the attenuated images.

22. A method of capturing a desired image comprising:

   a) creating a plurality of attenuated images of the image, each at an attenuation level that is different from the attenuation level of the other attenuated images; and

   b) simultaneously capturing all of the attenuated images.

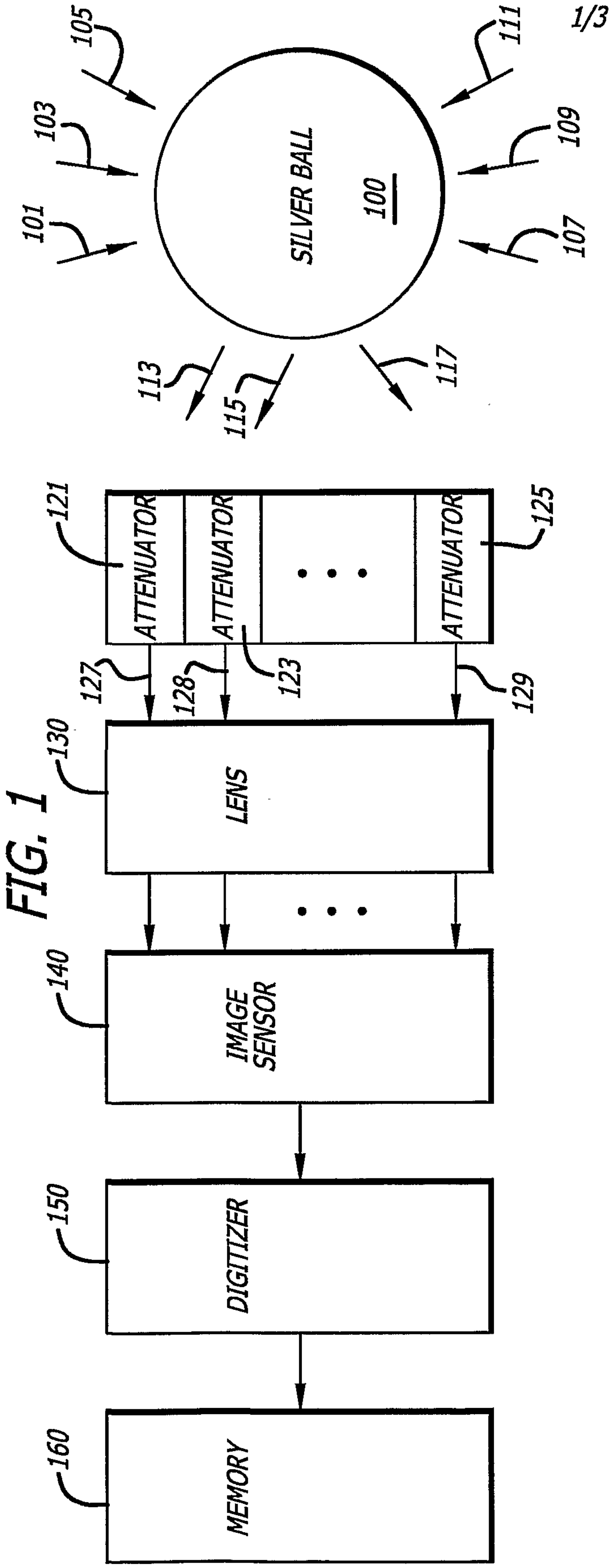

1/3
SILVER BALL
100
101
103
105
107
109
111
113
115
117
121
ATTENUATOR
ATTENUATOR
ATTENUATOR
123
125
127
128
129
130
LENS
140
IMAGE SENSOR
150
DIGITIZER
160
MEMORY

FIG. 1

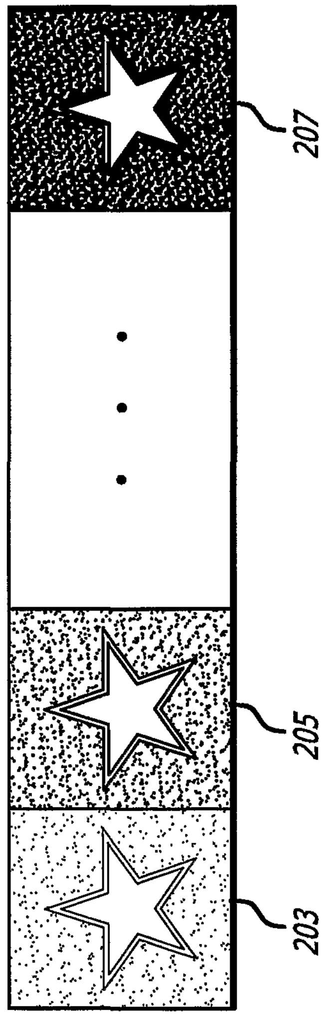

207
205
203

FIG. 2

2/3

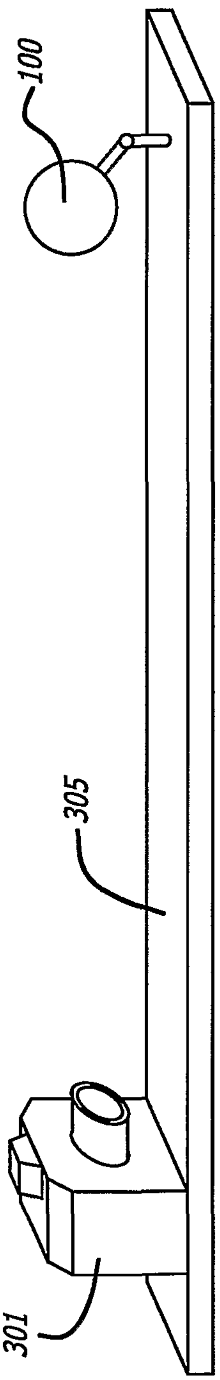


FIG. 3

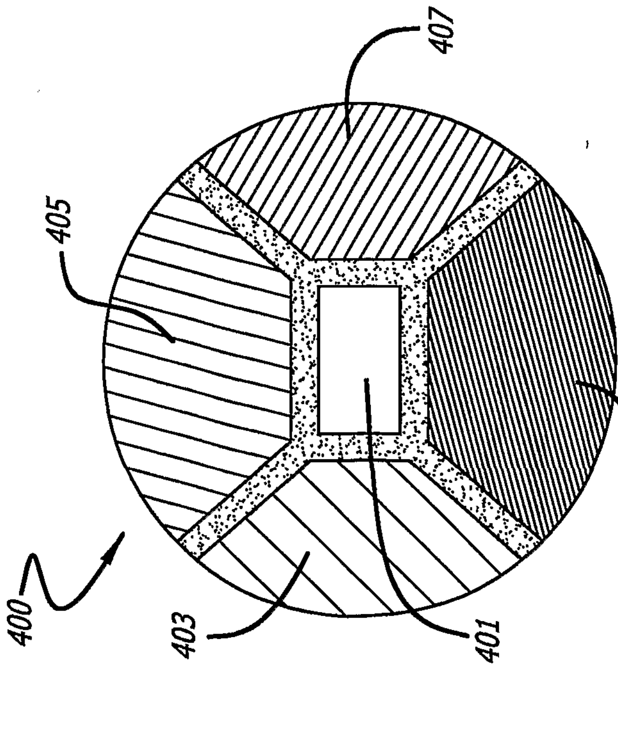


FIG. 4

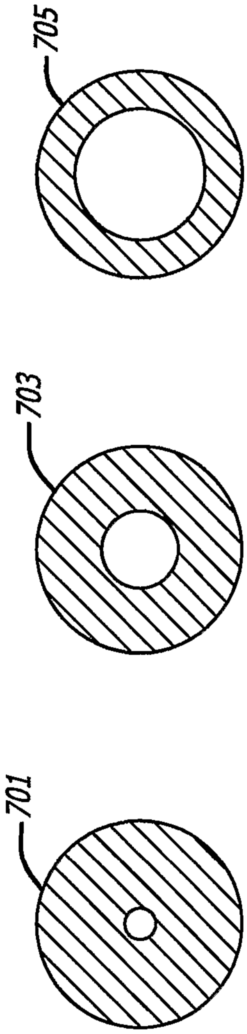


FIG. 7(a) FIG. 7(b) FIG. 7(c)

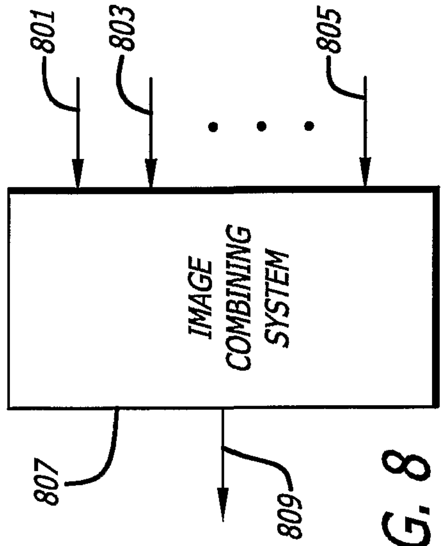


FIG. 8

3/3

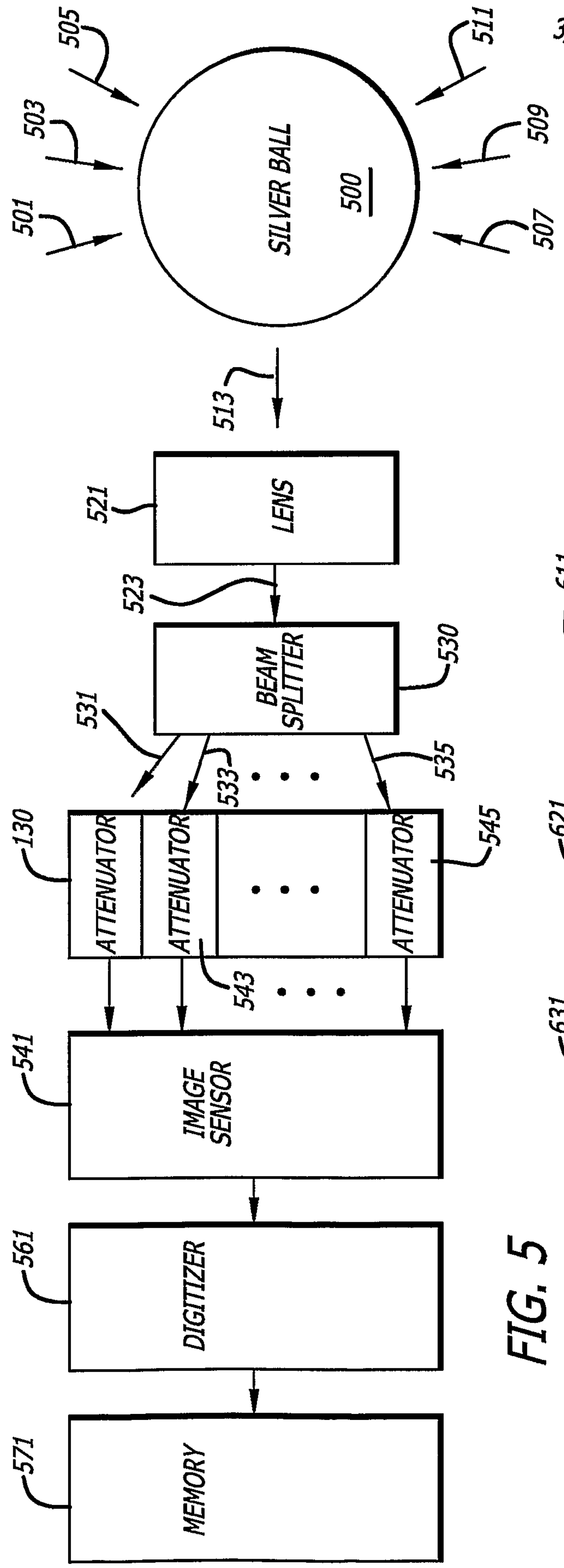

505
511
503
509
501
507
SILVER BALL
500
513
521
LENS
523
BEAM SPLITTER
530
531
533
535
130
ATTENUATOR
ATTENUATOR
ATTENUATOR
545
543
541
IMAGE SENSOR
561
DIGITIZER
571
MEMORY

FIG. 5

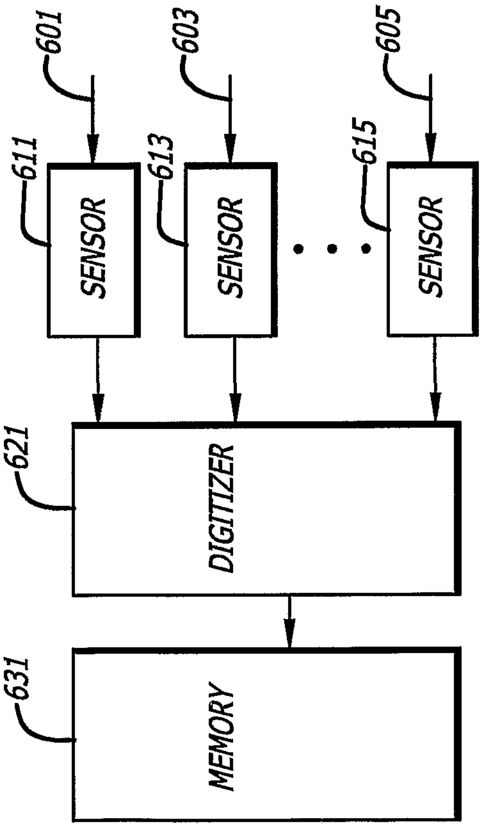

601
603
605
611
613
615
SENSOR
SENSOR
SENSOR
621
DIGITIZER
631
MEMORY

FIG. 6