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Sato et al.

(54) **IMAGE PROCESSING APPARATUS, IMAGE DIVISION PROGRAM AND IMAGE SYNTHESISING METHOD**

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(52) **U.S. Cl.** **348/335**; 348/E05.025

(57) **ABSTRACT**

A polarization image capturing section **103** obtains a first polarization image containing polarization information. A polarization information obtaining section **104** obtains first polarization information from the first polarization image. An illumination control section **102** changes an illumination section **101** and again obtains a second polarization image by means of the polarization image capturing section **103**. The polarization information obtaining section **104** obtains second polarization information from the second polarization image. A light source dependency estimation section **105** obtains light source dependency from the first and second polarization information obtained from the first and second polarization images. An area dividing section **106** performs an area division by using the polarization information and light source dependency information.

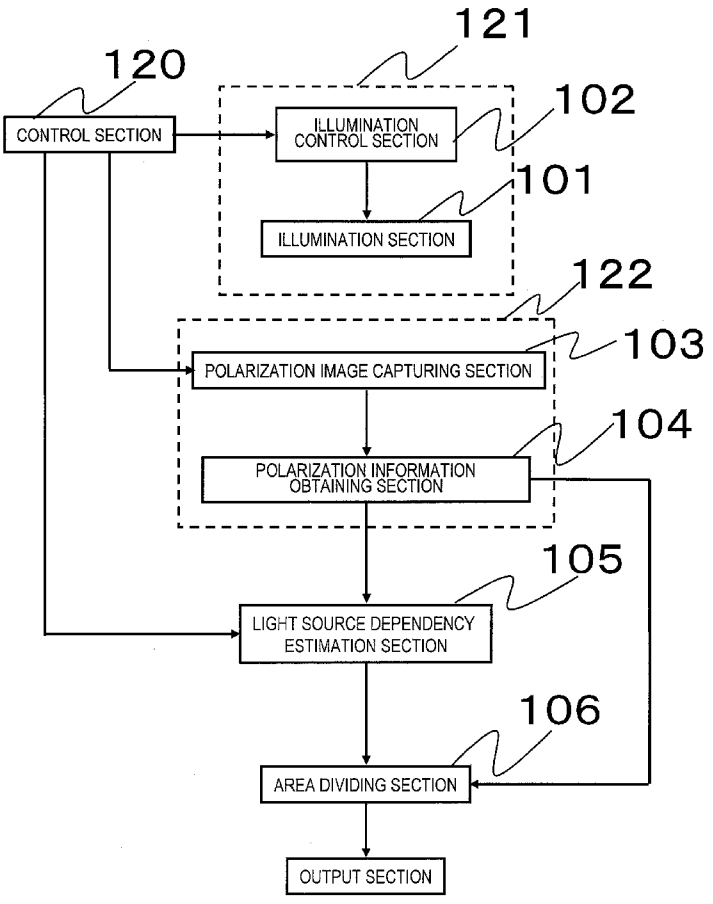


FIG. 1

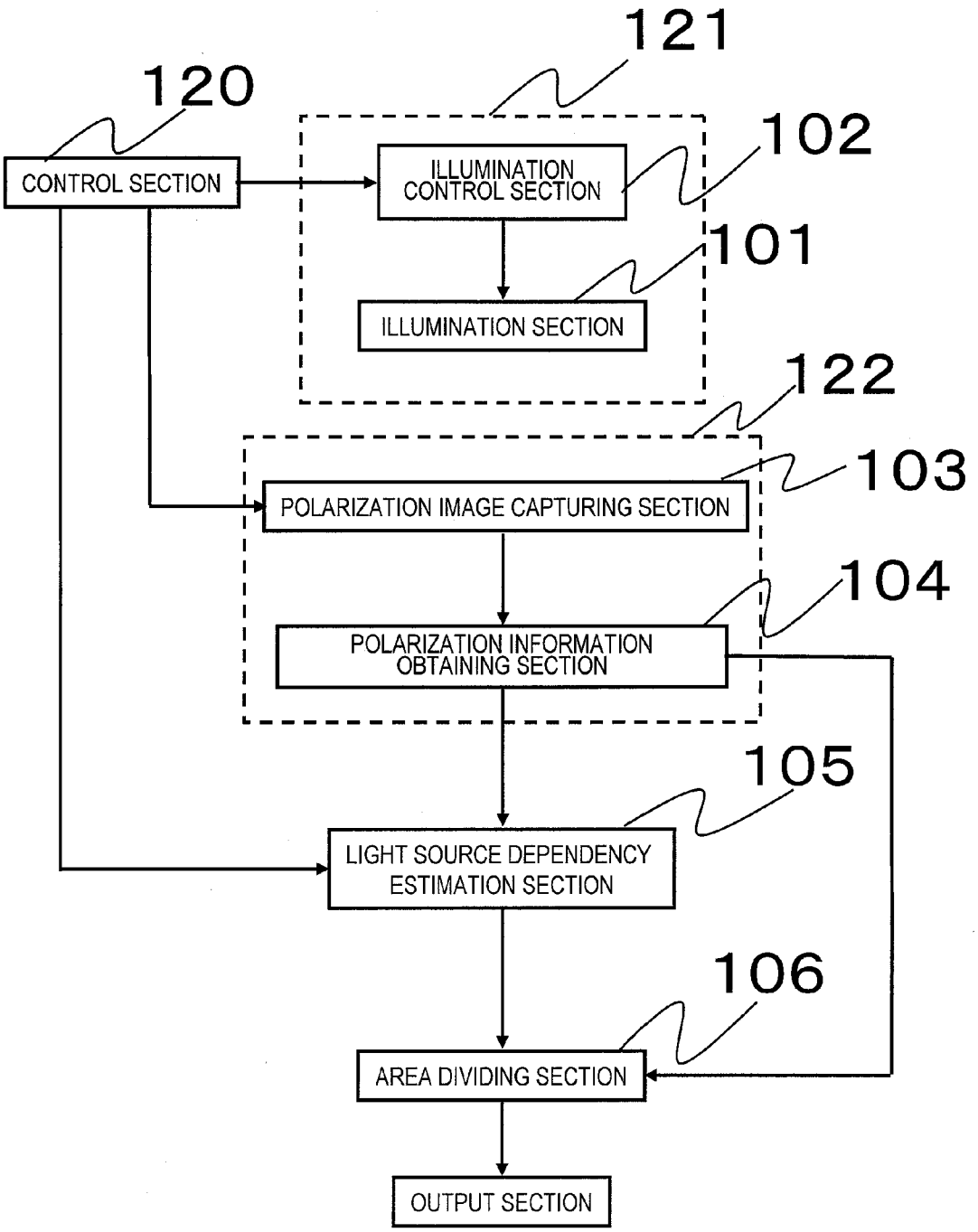

121
120
102
CONTROL SECTION
ILLUMINATION CONTROL SECTION
101
ILLUMINATION SECTION
122
103
POLARIZATION IMAGE CAPTURING SECTION
104
POLARIZATION INFORMATION OBTAINING SECTION
105
LIGHT SOURCE DEPENDENCY ESTIMATION SECTION
106
AREA DIVIDING SECTION
OUTPUT SECTION

FIG. 2

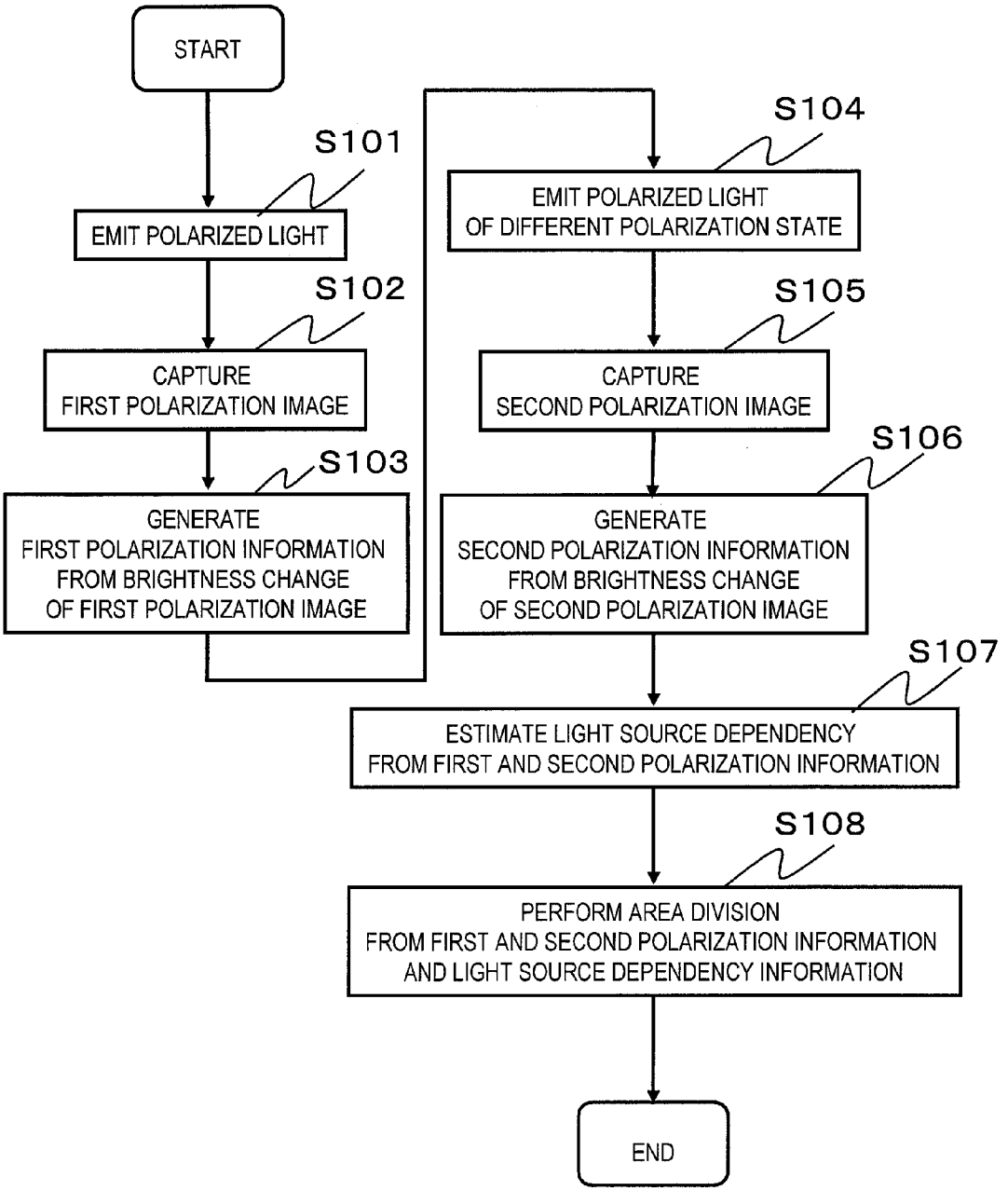

START
S101
EMIT POLARIZED LIGHT
S102
CAPTURE
FIRST POLARIZATION IMAGE
S103
GENERATE
FIRST POLARIZATION INFORMATION
FROM BRIGHTNESS CHANGE
OF FIRST POLARIZATION IMAGE
S104
EMIT POLARIZED LIGHT
OF DIFFERENT POLARIZATION STATE
S105
CAPTURE
SECOND POLARIZATION IMAGE
S106
GENERATE
SECOND POLARIZATION INFORMATION
FROM BRIGHTNESS CHANGE
OF SECOND POLARIZATION IMAGE
S107
ESTIMATE LIGHT SOURCE DEPENDENCY
FROM FIRST AND SECOND POLARIZATION INFORMATION
S108
PERFORM AREA DIVISION
FROM FIRST AND SECOND POLARIZATION INFORMATION
AND LIGHT SOURCE DEPENDENCY INFORMATION
END

FIG. 3

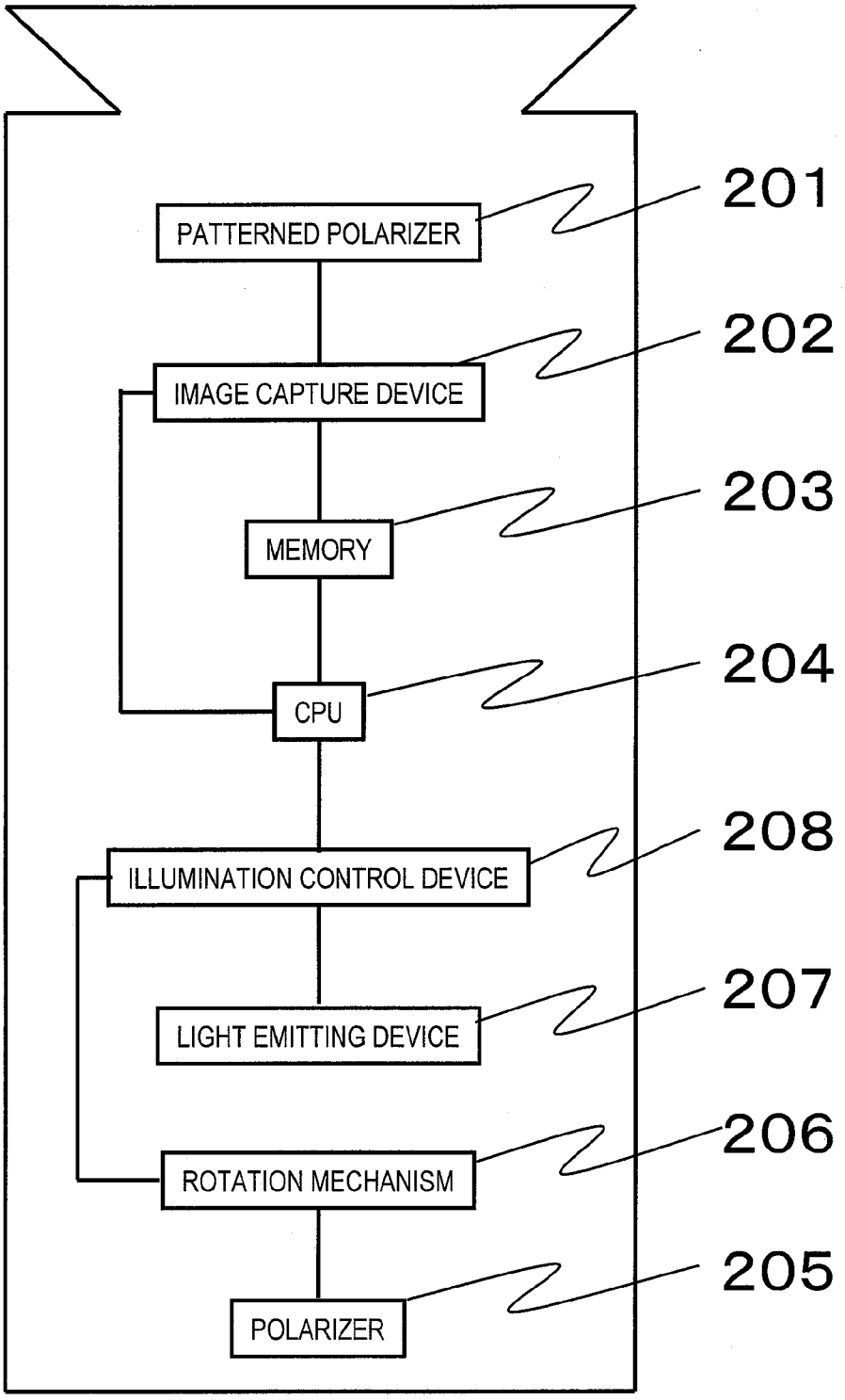

PATTERNED POLARIZER
201
IMAGE CAPTURE DEVICE
202
MEMORY
203
CPU
204
ILLUMINATION CONTROL DEVICE
208
LIGHT EMITTING DEVICE
207
ROTATION MECHANISM
206
POLARIZER
205

FIG. 4

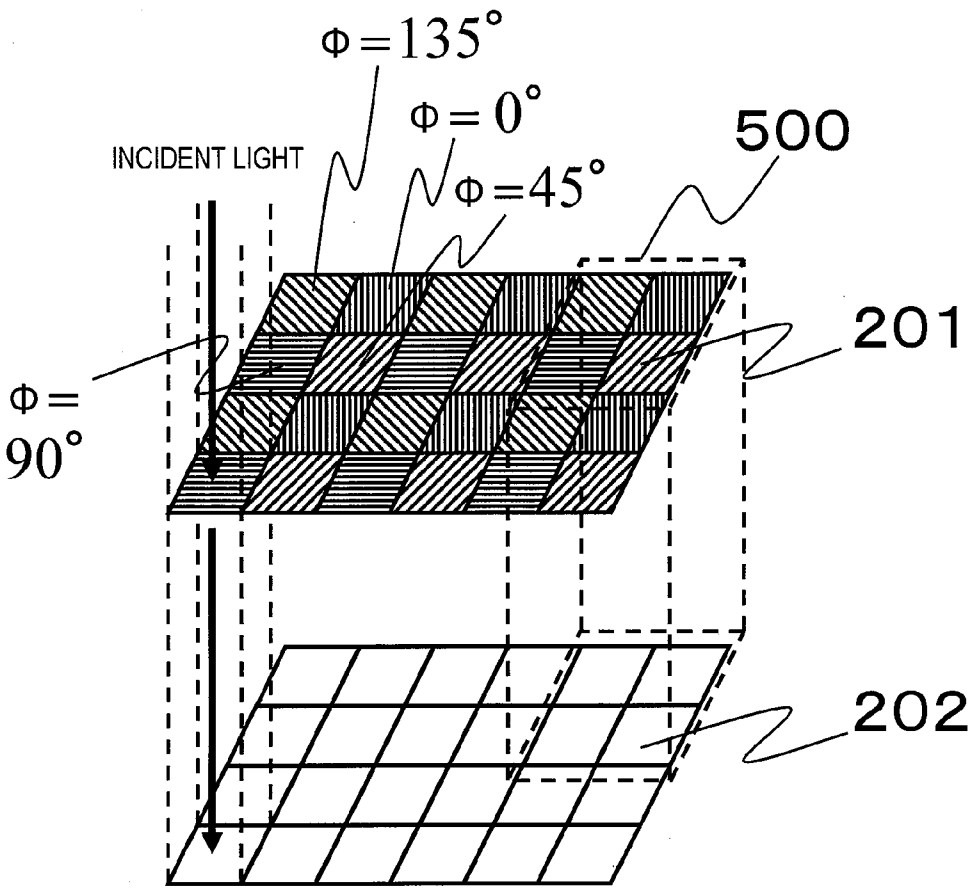


FIG. 5

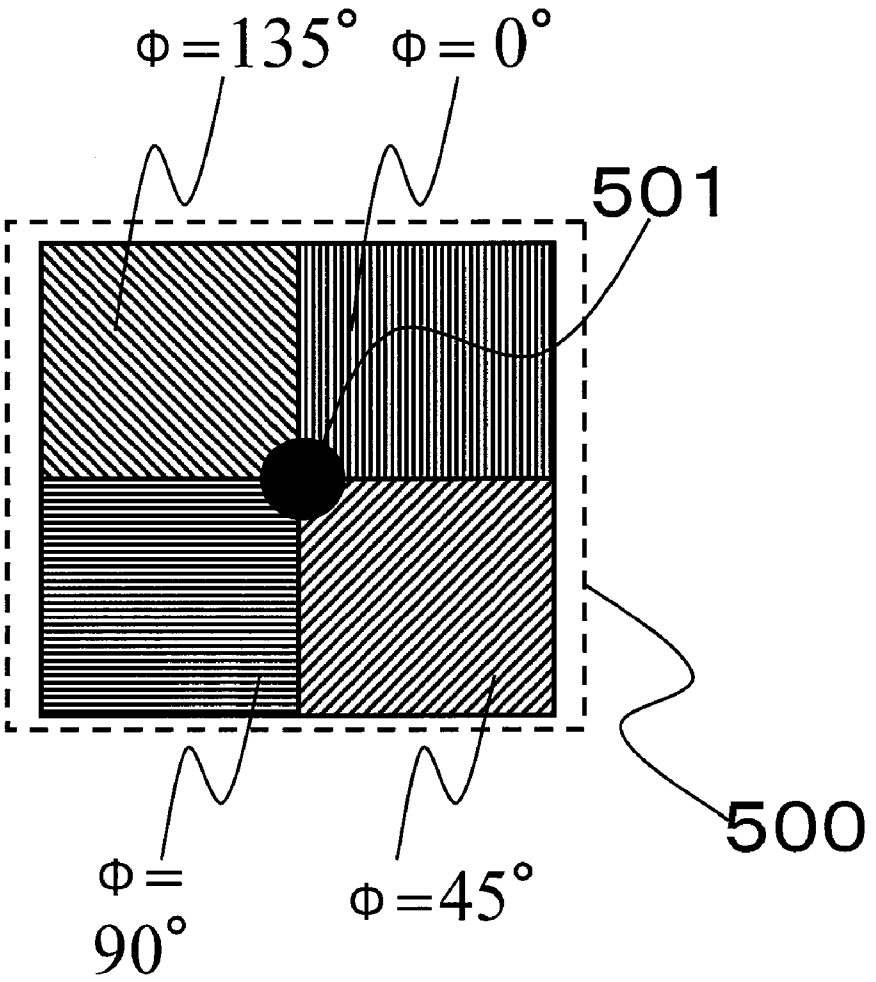


FIG. 6

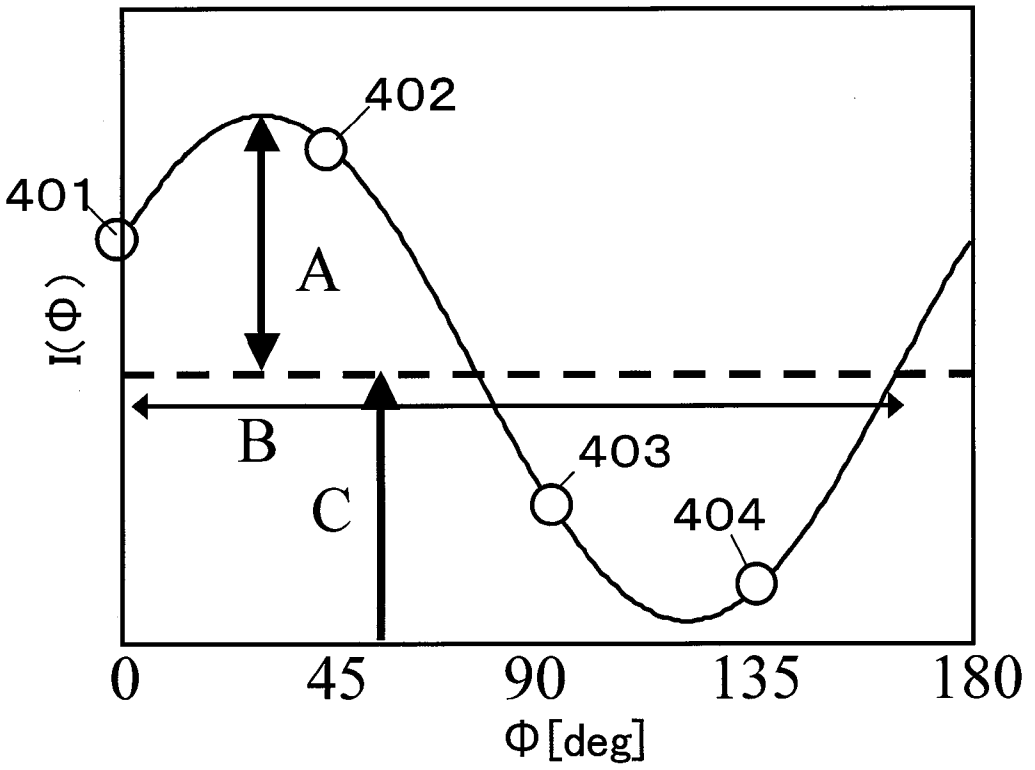


FIG. 7

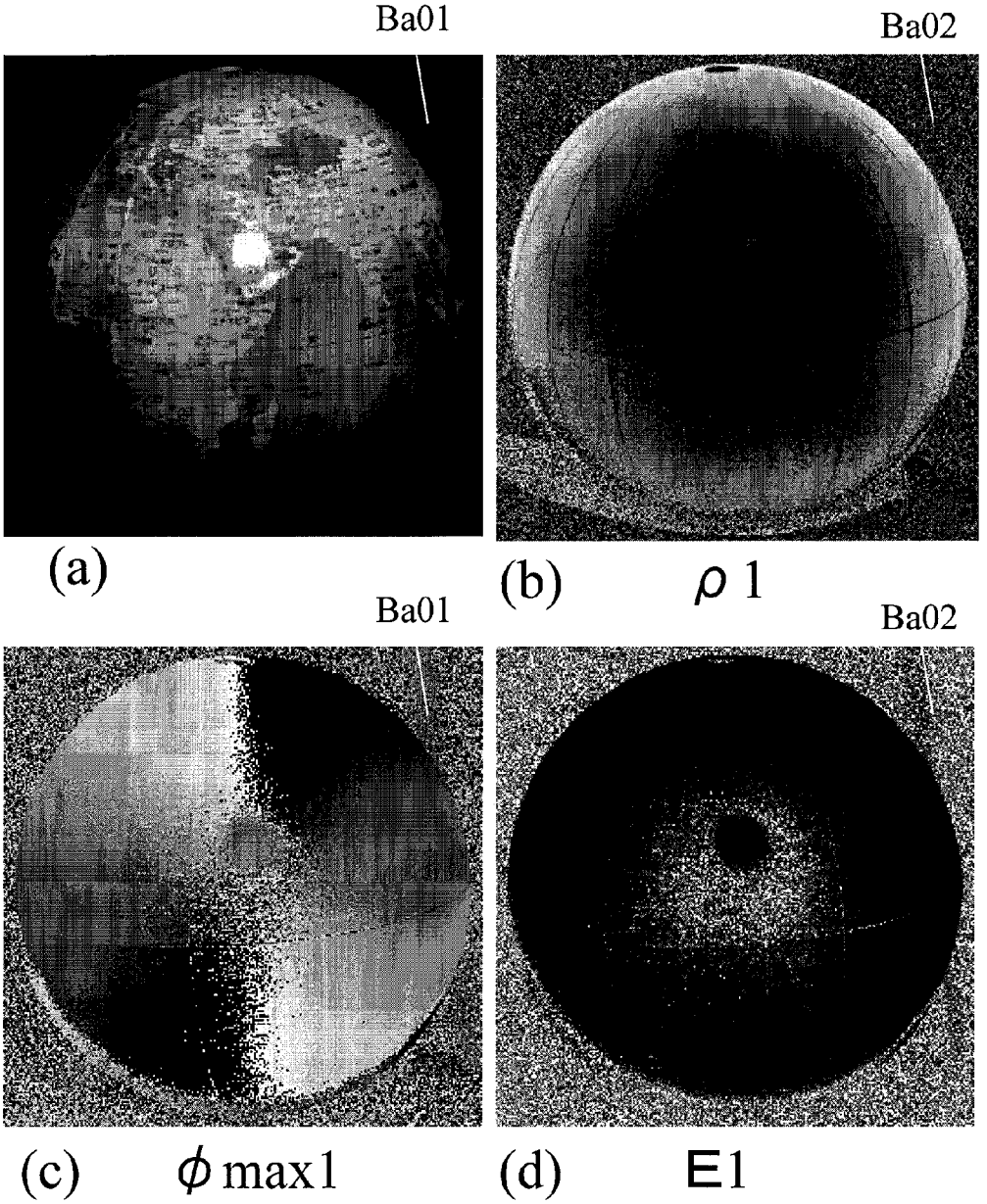


FIG. 8

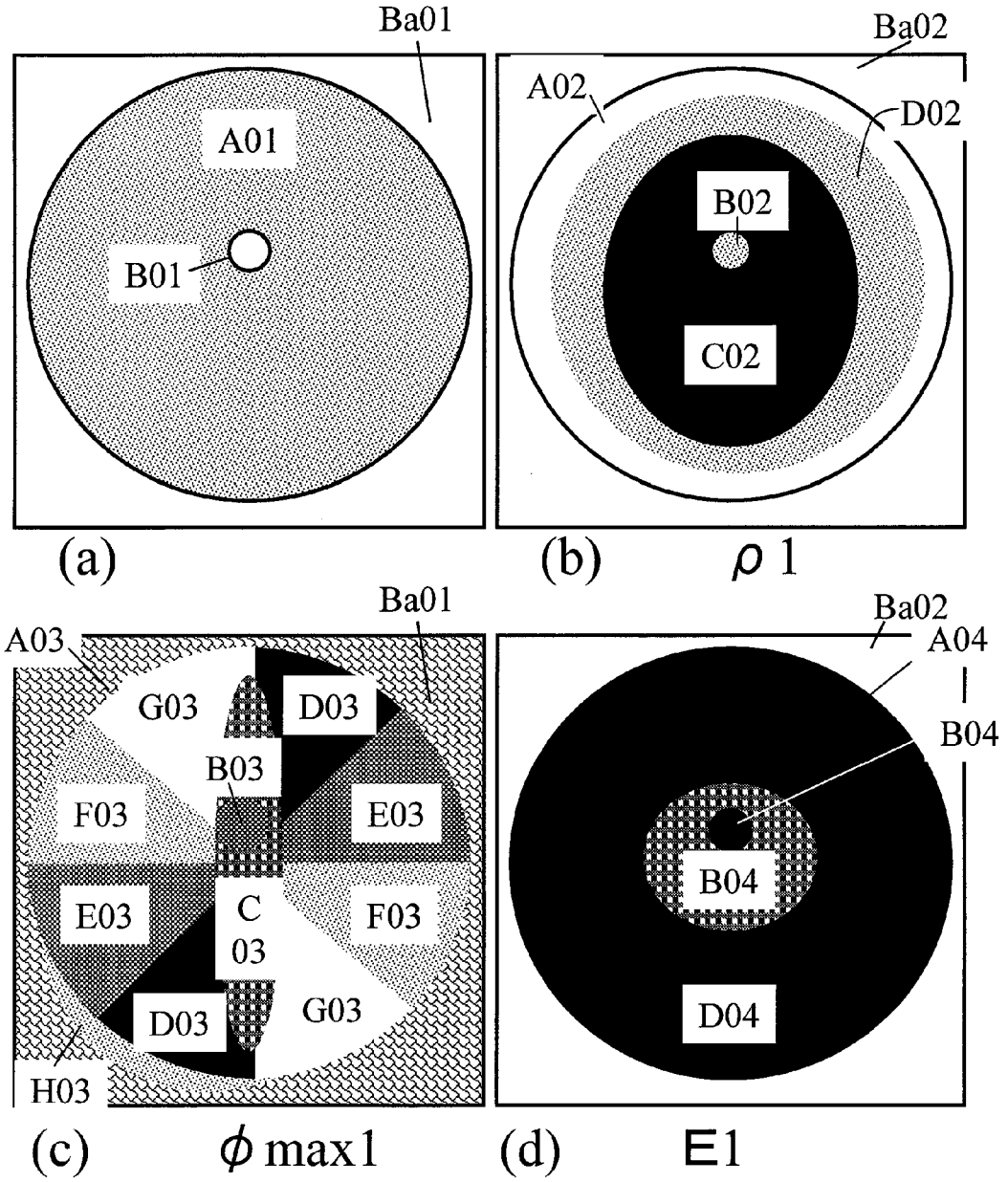

Ba01
A01
B01
(a)
Ba02
A02
D02
B02
C02
(b) ρ 1
Ba01
A03
G03
D03
B03
F03
E03
E03
C
03
F03
D03
G03
H03
(c) φ max1
Ba02
A04
B04
B04
D04
(d) E1

FIG. 9

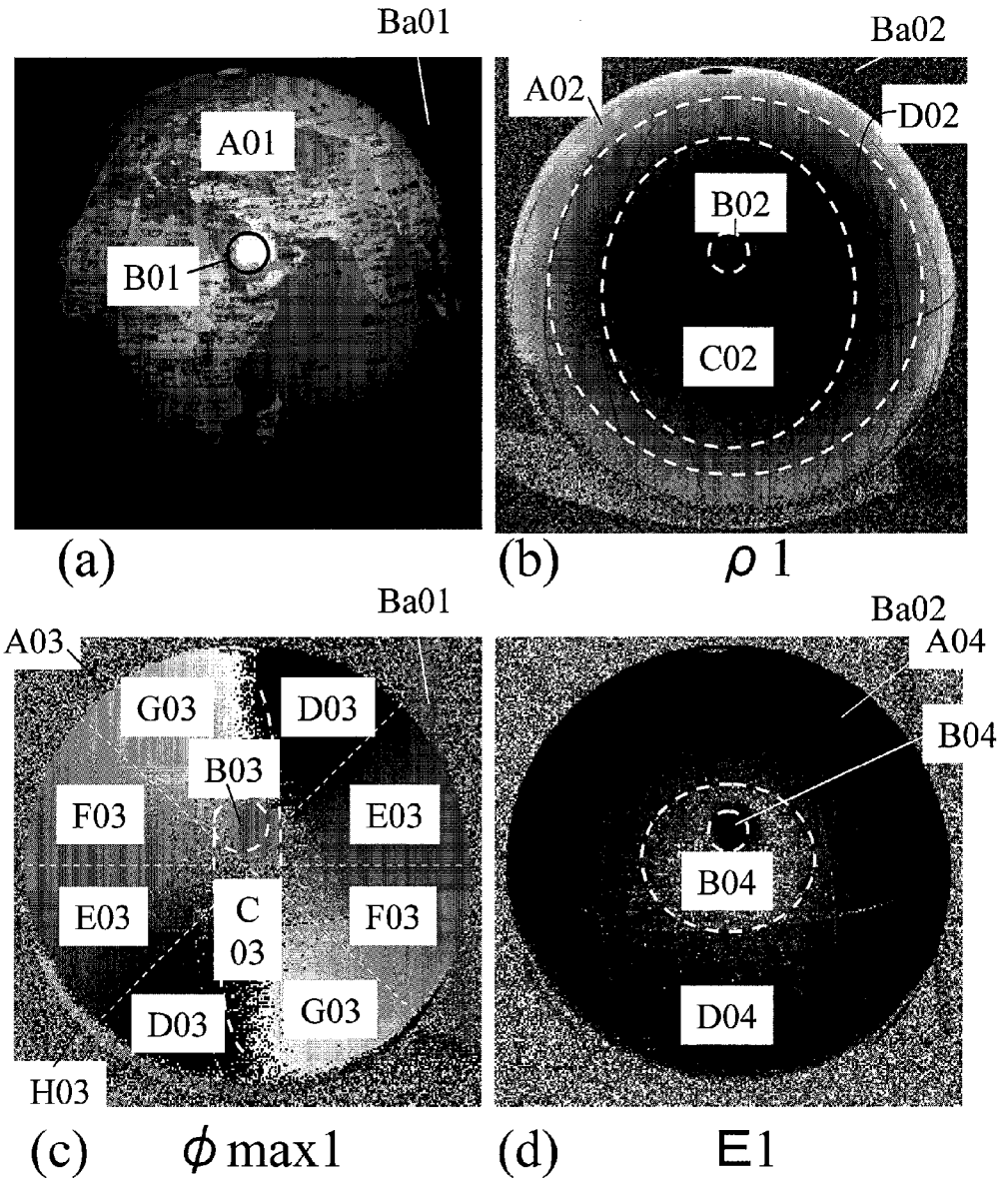

Ba01
A01
B01
(a)
Ba02
A02
D02
B02
C02
(b) ρ1
Ba01
A03
G03
D03
B03
F03
E03
E03
C
03
F03
D03
G03
H03
(c) φmax1
Ba02
A04
B04
B04
D04
(d) E1

FIG. 10

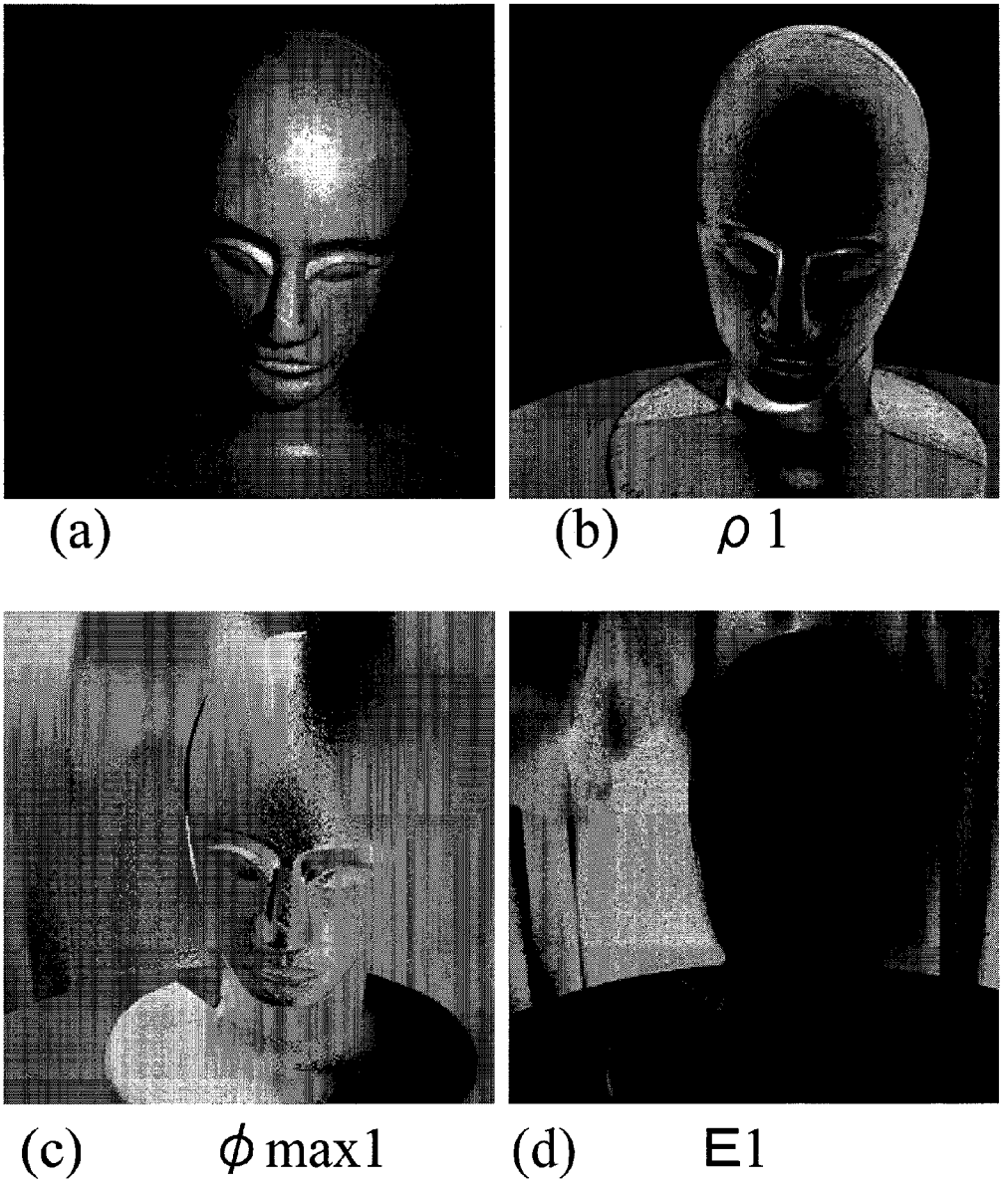


FIG. 11

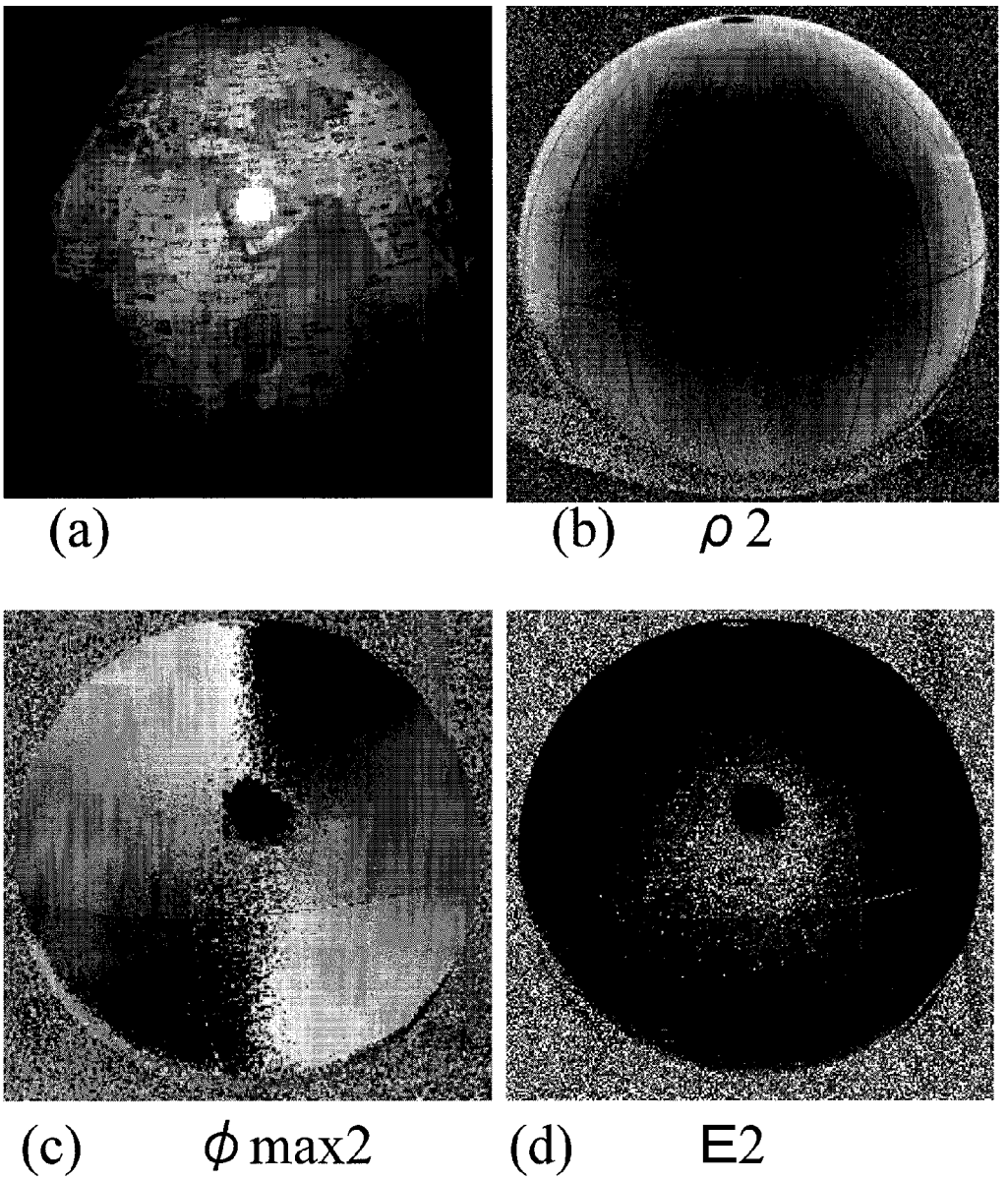


FIG. 12

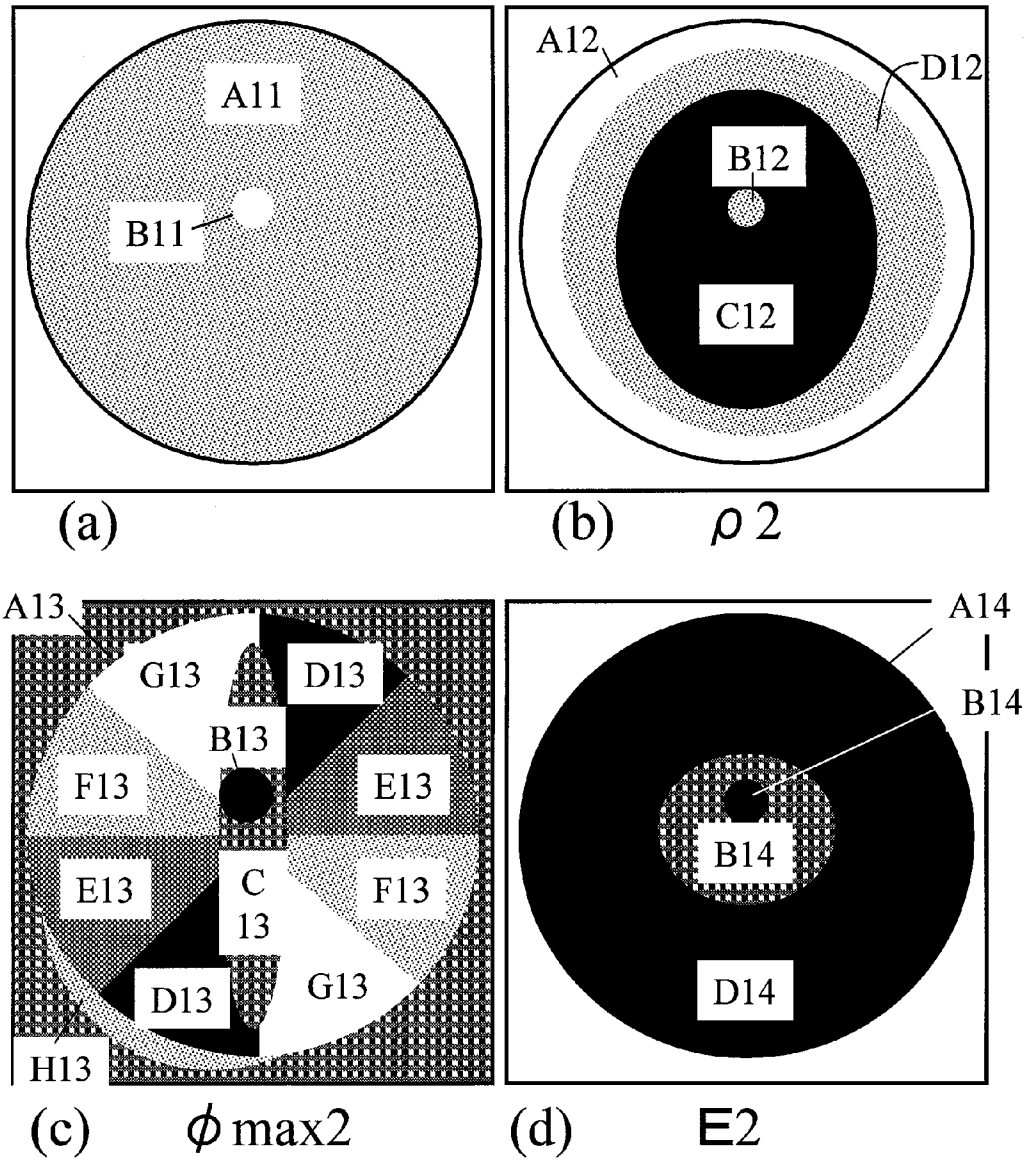

A11
B11
A12
D12
B12
C12
(a)
(b) ρ2
A13
G13
D13
B13
F13
E13
E13
C
13
F13
D13
G13
H13
A14
B14
B14
D14
(c) φmax2
(d) E2

FIG. 13

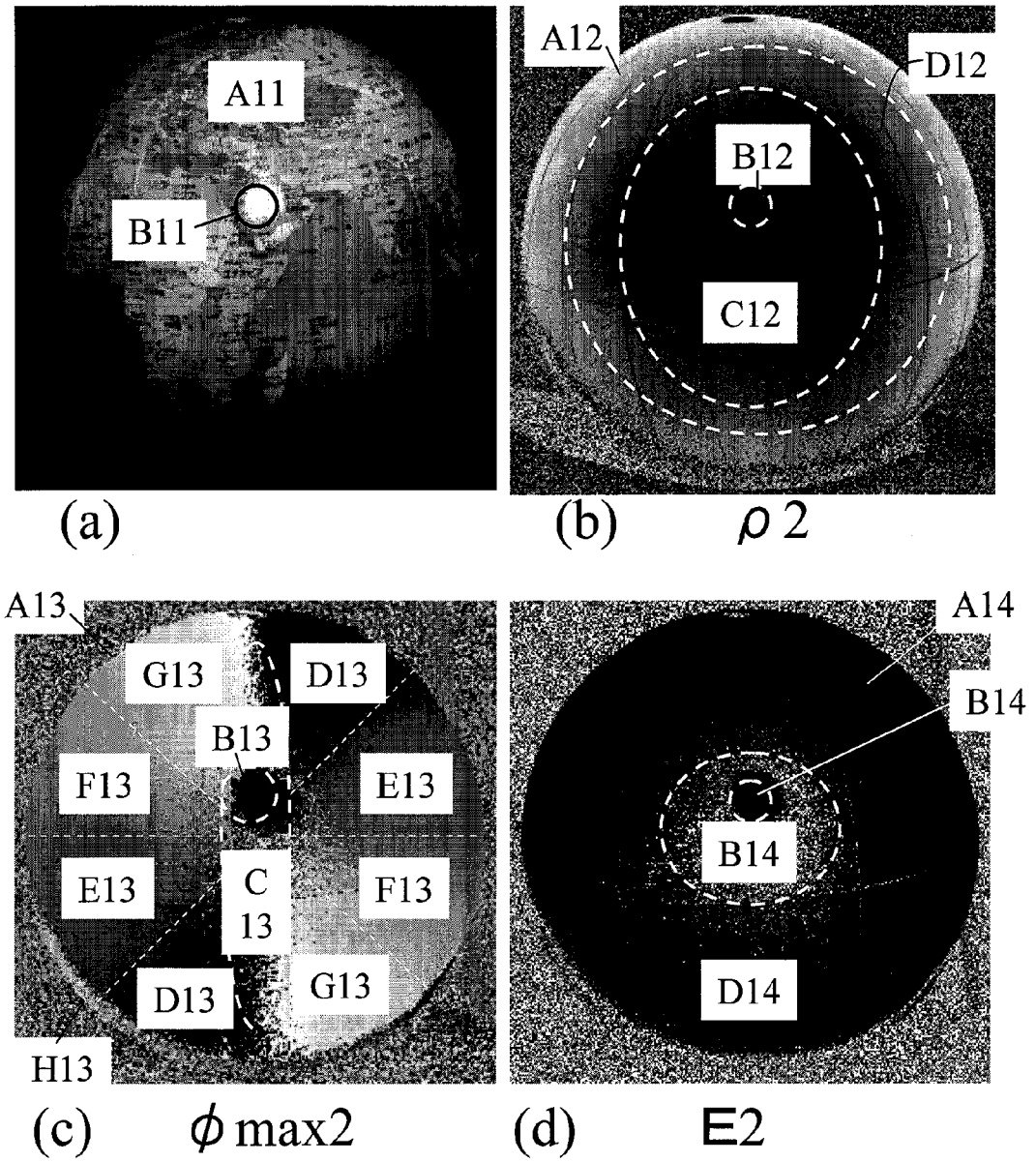

A11
B11
(a)
A12
D12
B12
C12
(b) ρ2
A13
G13
D13
B13
F13
E13
E13
C
13
F13
D13
G13
H13
(c) φmax2
A14
B14
B14
D14
(d) E2

FIG. 14

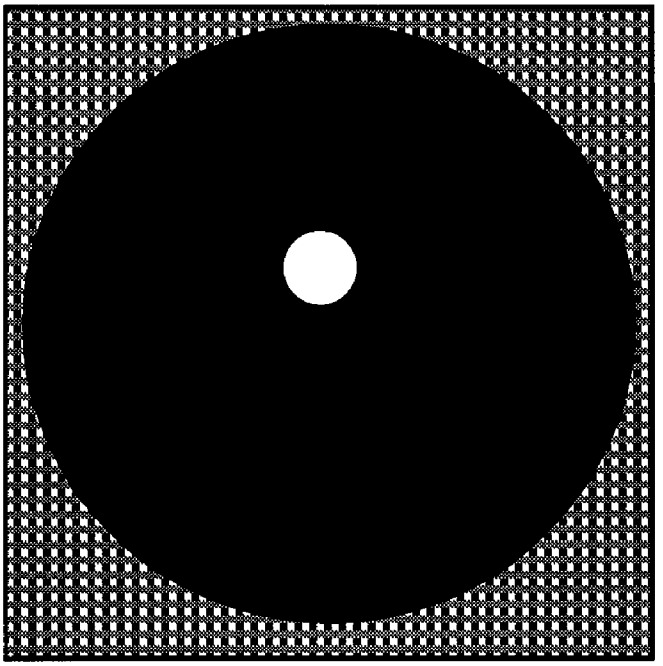
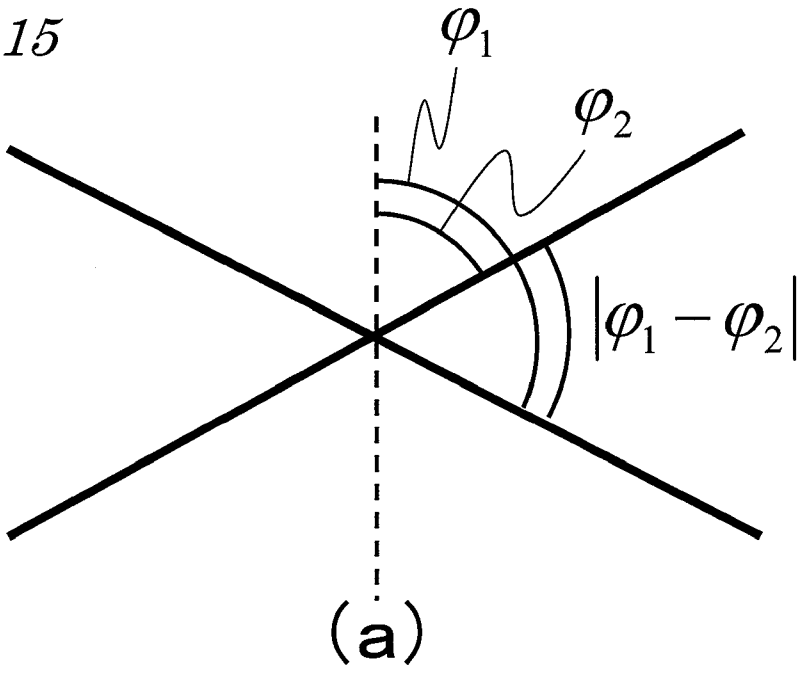
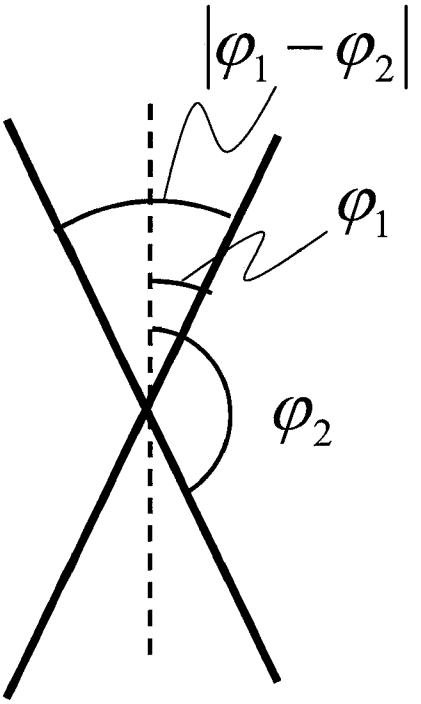


FIG. 15


φ_1
φ_2
$|\varphi_1 - \varphi_2|$

(a)


$|\varphi_1 - \varphi_2|$
φ_1
φ_2

(b)

FIG. 16

		LIGHT SOURCE DEPENDENCY	
		HIGH	LOW
DEGREE OF POLARIZATION	HIGH	SPECULAR REFLECTION POLARIZED AREA	DIFFUSE REFLECTION POLARIZED AREA
	LOW	DIFFUSE REFLECTION NON-POLARIZED AREA	

FIG. 17

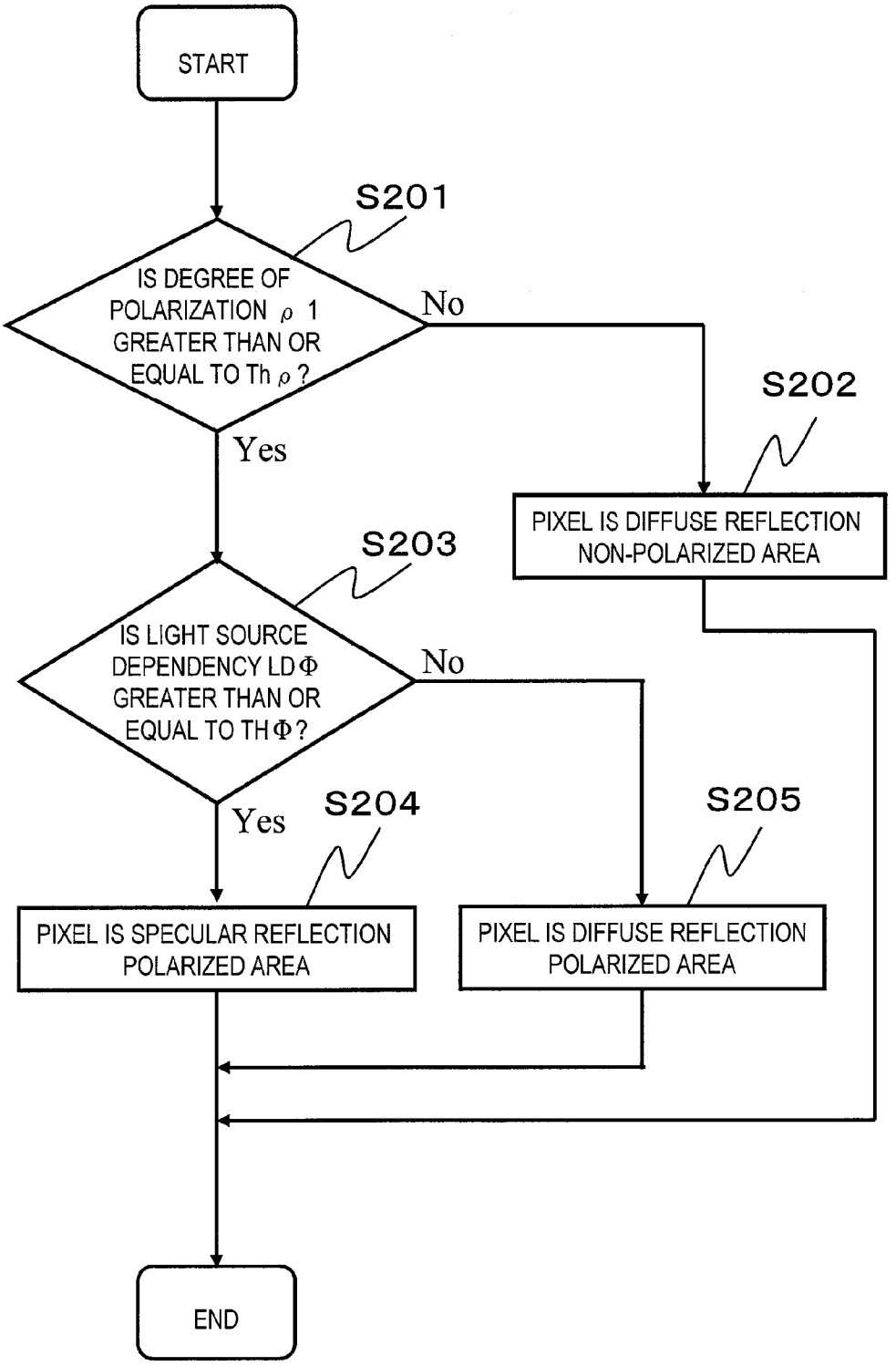

START
S201
IS DEGREE OF POLARIZATION ρ 1 GREATER THAN OR EQUAL TO Th ρ ?
No
Yes
S202
PIXEL IS DIFFUSE REFLECTION NON-POLARIZED AREA
S203
IS LIGHT SOURCE DEPENDENCY LDΦ GREATER THAN OR EQUAL TO THΦ?
No
Yes
S204
S205
PIXEL IS SPECULAR REFLECTION POLARIZED AREA
PIXEL IS DIFFUSE REFLECTION POLARIZED AREA
END

FIG. 18

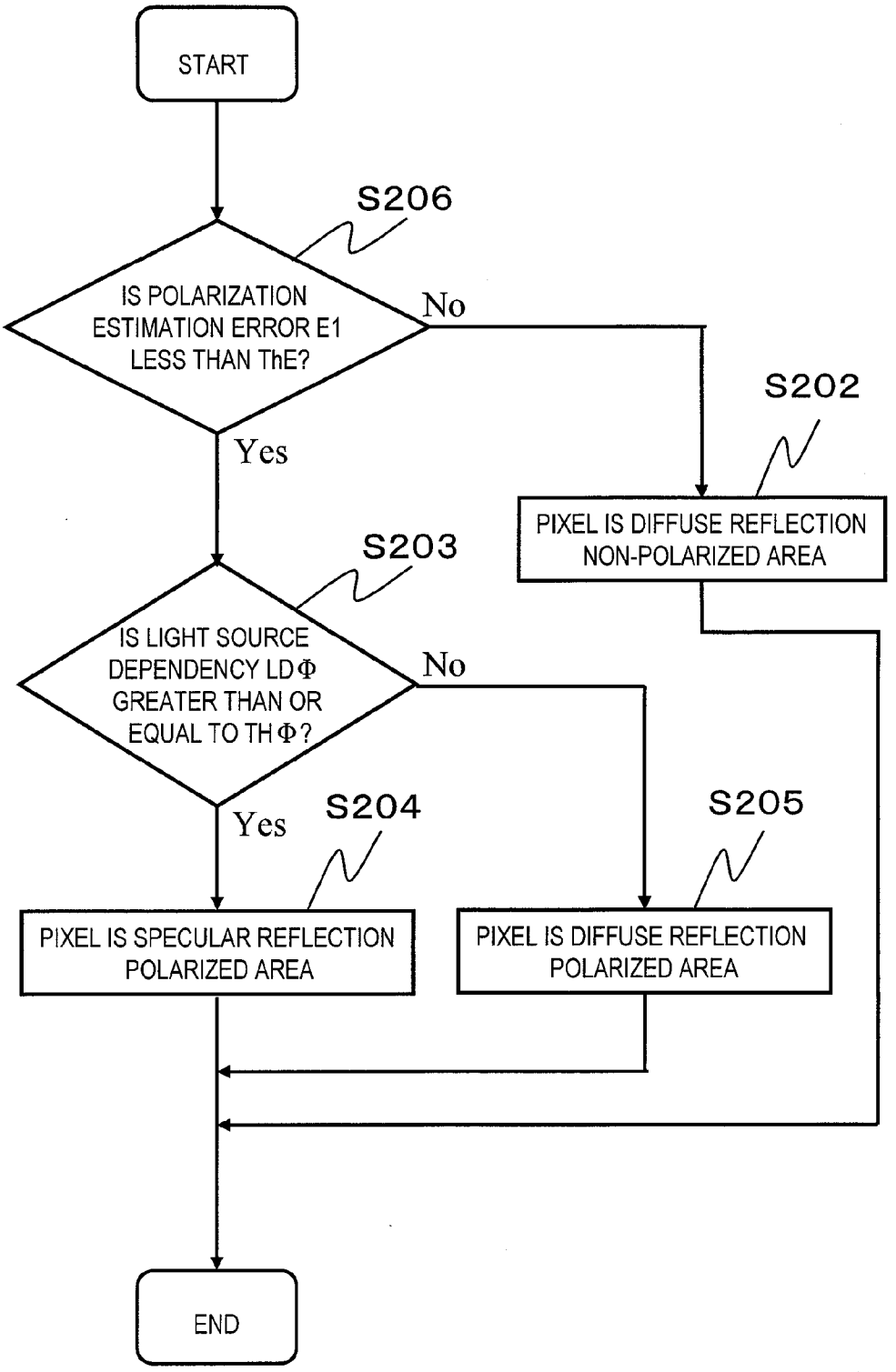

START
S206
IS POLARIZATION ESTIMATION ERROR E1 LESS THAN ThE?
No
Yes
S202
PIXEL IS DIFFUSE REFLECTION NON-POLARIZED AREA
S203
IS LIGHT SOURCE DEPENDENCY LDΦ GREATER THAN OR EQUAL TO THΦ?
No
Yes
S204
PIXEL IS SPECULAR REFLECTION POLARIZED AREA
S205
PIXEL IS DIFFUSE REFLECTION POLARIZED AREA
END

FIG. 19

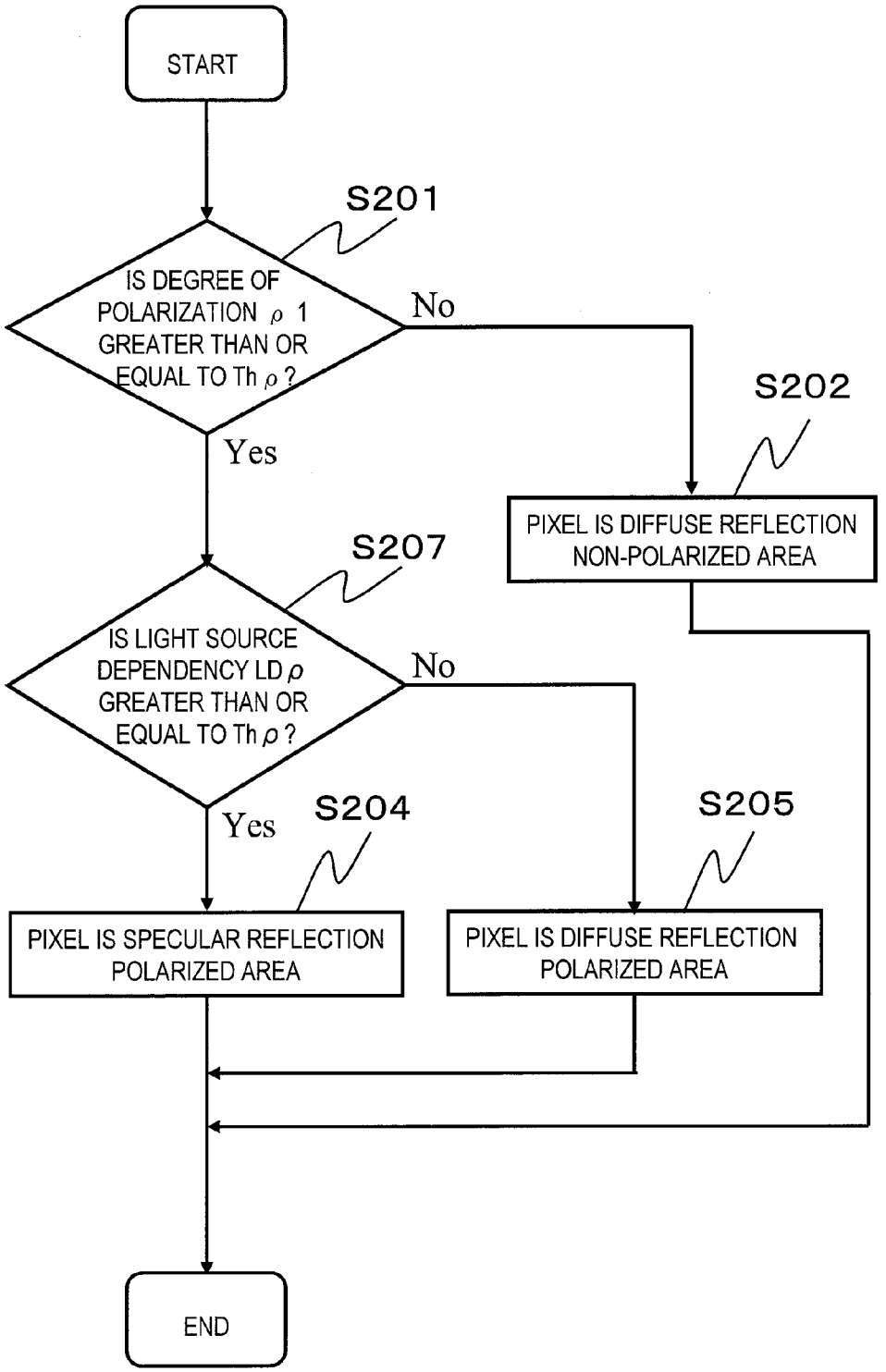
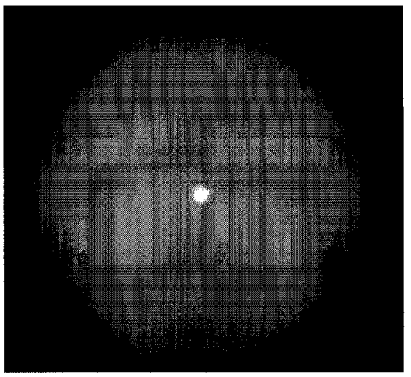
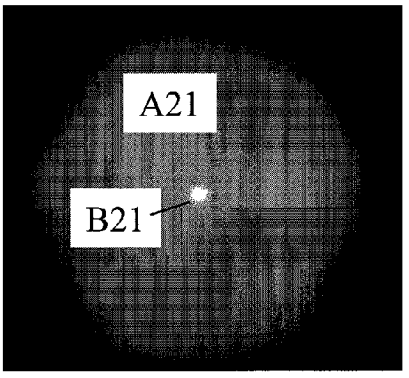

START
S201
IS DEGREE OF POLARIZATION ρ 1 GREATER THAN OR EQUAL TO Th ρ ?
No
Yes
S202
PIXEL IS DIFFUSE REFLECTION NON-POLARIZED AREA
S207
IS LIGHT SOURCE DEPENDENCY LD ρ GREATER THAN OR EQUAL TO Th ρ ?
No
Yes
S204
S205
PIXEL IS SPECULAR REFLECTION POLARIZED AREA
PIXEL IS DIFFUSE REFLECTION POLARIZED AREA
END

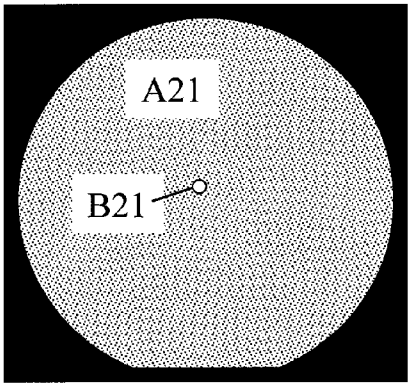
FIG. 20



(a)



(b)



(c)

FIG. 21

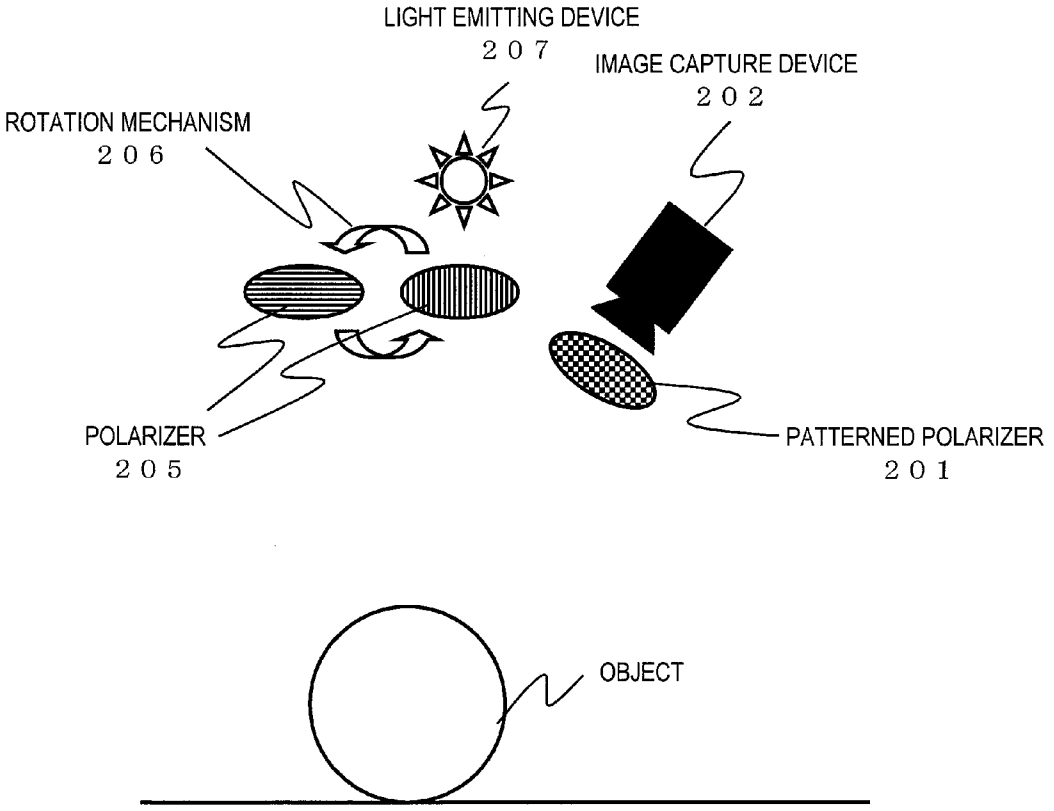
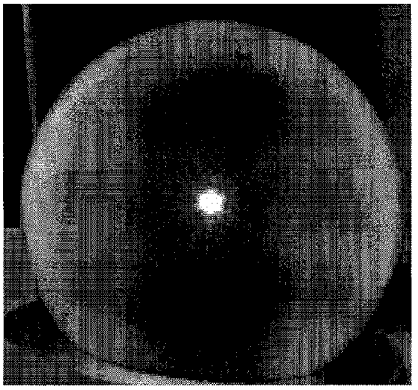
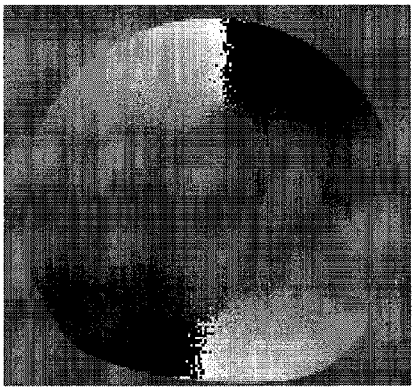

LIGHT EMITTING DEVICE
207
IMAGE CAPTURE DEVICE
202
ROTATION MECHANISM
206
POLARIZER
205
PATTERNED POLARIZER
201
OBJECT

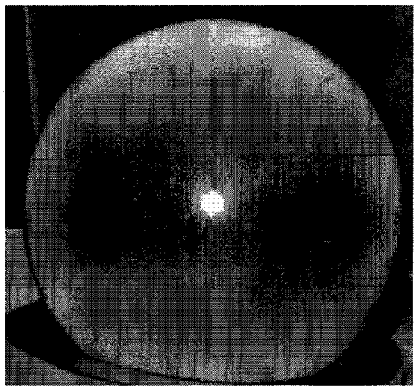
FIG. 22



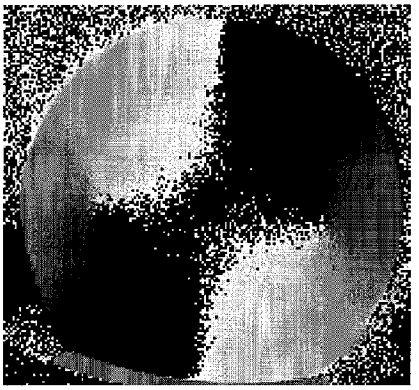
(a) $\rho 1$
(POLARIZATION AXIS IS HORIZONTAL)



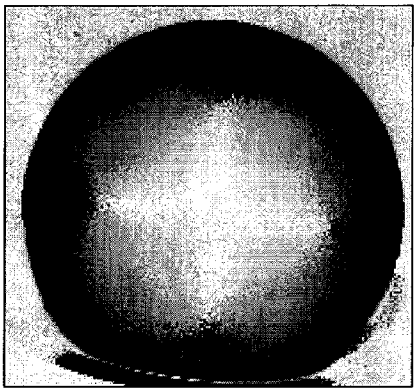
(b) $\phi max1$
(POLARIZATION AXIS IS HORIZONTAL)



(c) $\rho 2$
(POLARIZATION AXIS IS VERTICAL)



(d) $\phi max2$
(POLARIZATION AXIS IS VERTICAL)



(e) LD ϕ

FIG. 23

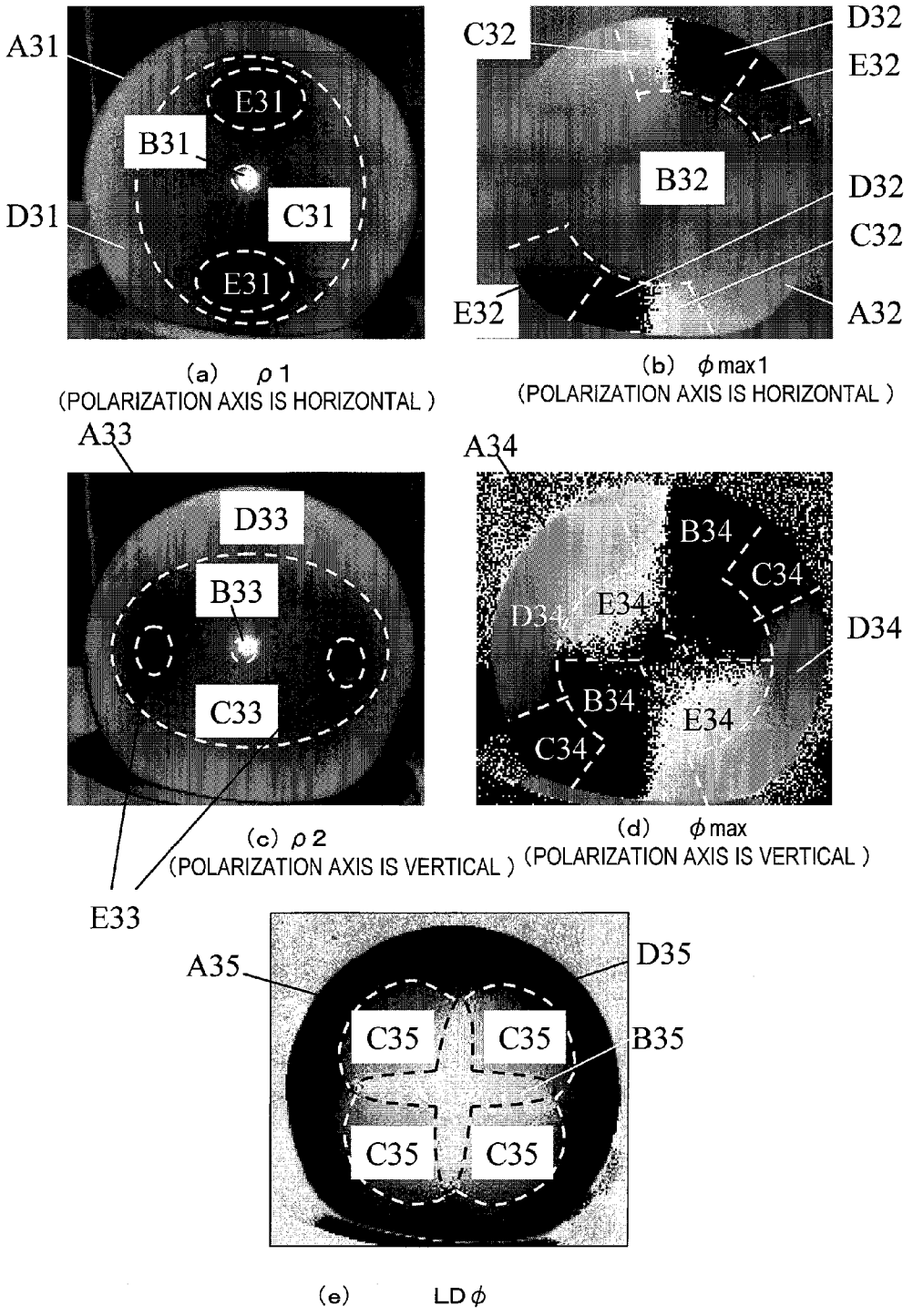

A31
E31
B31
C31
D31
E31
(a) ρ1
(POLARIZATION AXIS IS HORIZONTAL)
C32
D32
E32
B32
D32
C32
E32
A32
(b) φmax1
(POLARIZATION AXIS IS HORIZONTAL)
A33
D33
B33
C33
E33
(c) ρ2
(POLARIZATION AXIS IS VERTICAL)
A34
B34
C34
D34
E34
D34
B34
E34
C34
(d) φmax
(POLARIZATION AXIS IS VERTICAL)
A35
D35
C35
C35
B35
C35
C35
(e) LDφ

FIG. 24

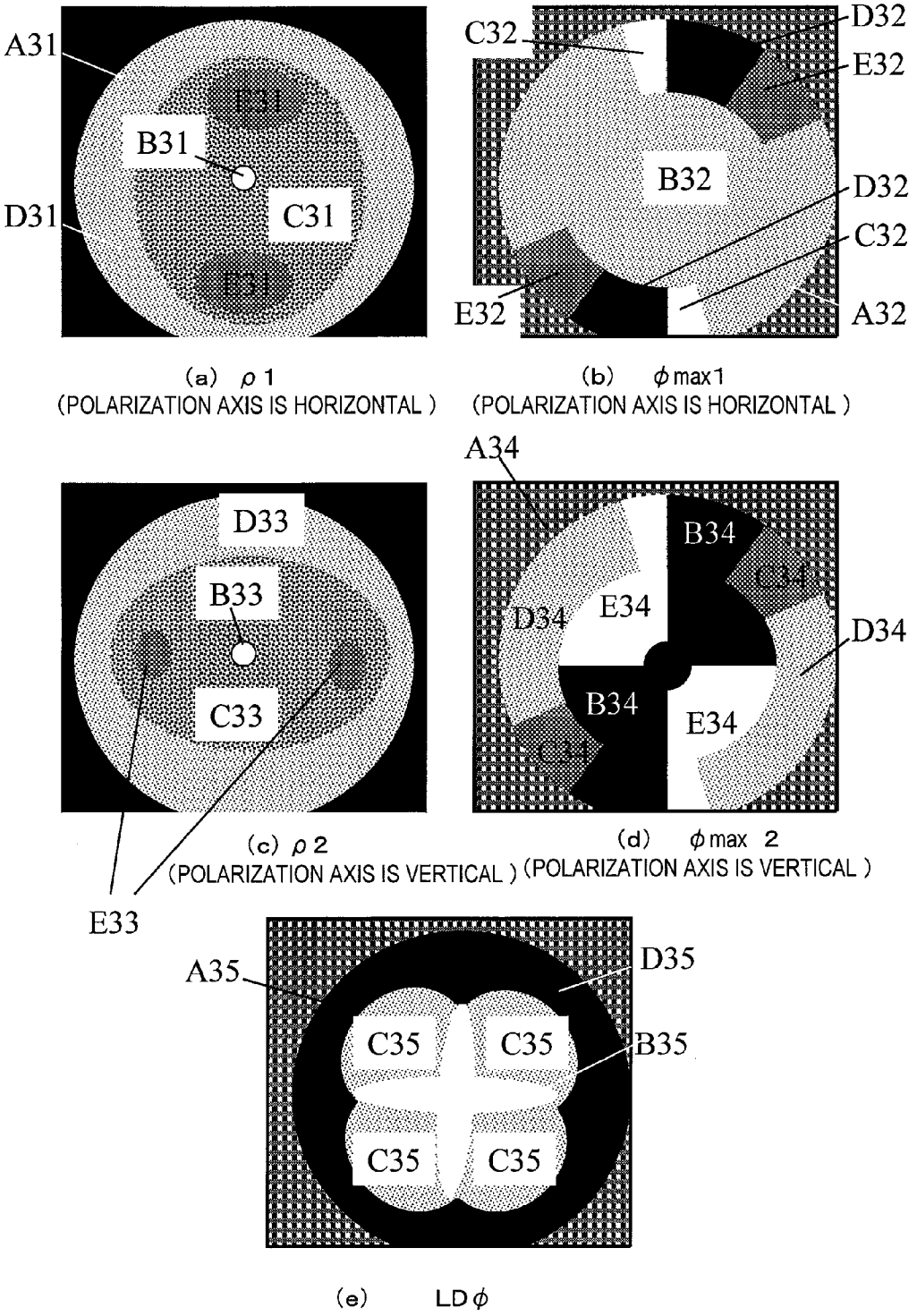
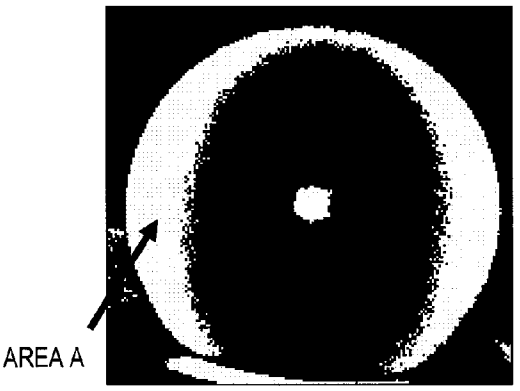
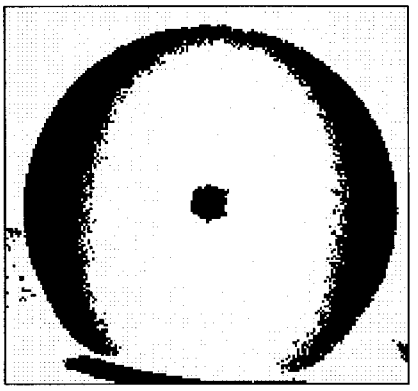

A31
B31
C31
D31
E31
C32
D32
E32
B32
D32
C32
E32
A32
(a) ρ1
(POLARIZATION AXIS IS HORIZONTAL)
(b) φmax1
(POLARIZATION AXIS IS HORIZONTAL)
A34
D33
B33
C33
E33
B34
C34
D34
E34
D34
B34
E34
C34
(c) ρ2
(POLARIZATION AXIS IS VERTICAL)
(d) φmax 2
(POLARIZATION AXIS IS VERTICAL)
A35
D35
C35
C35
B35
C35
C35
(e) LDφ

FIG. 25

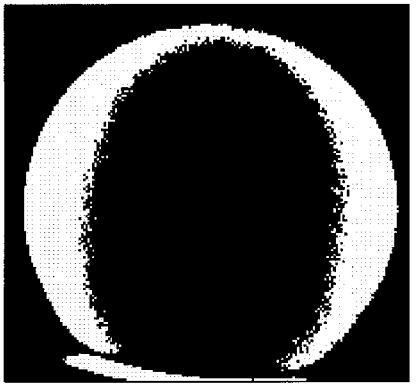


(a) $\rho 1 \geqq Th\rho$

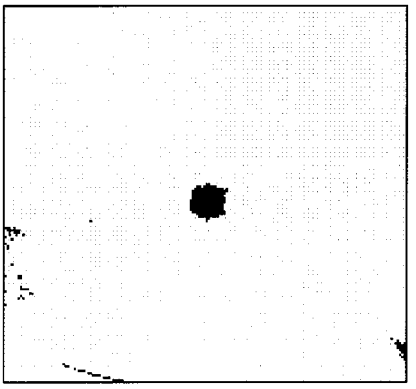


(b) DIFFUSE REFLECTION NON-POLARIZED AREA

(c) SPECULAR REFLECTION POLARIZED AREA

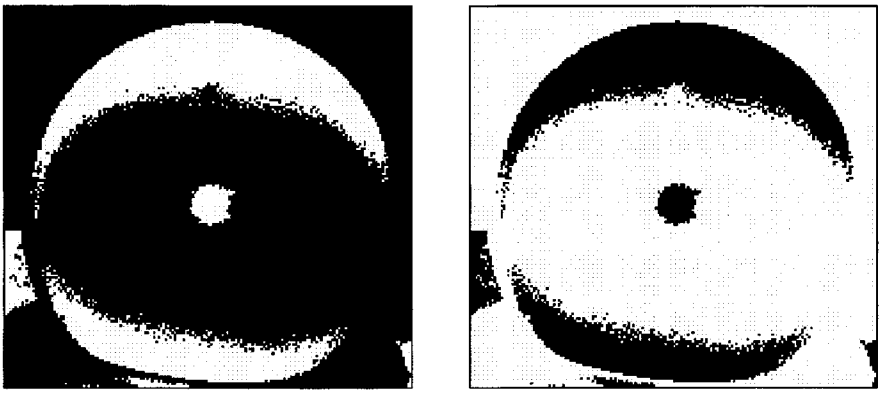


(d) DIFFUSE REFLECTION POLARIZED AREA



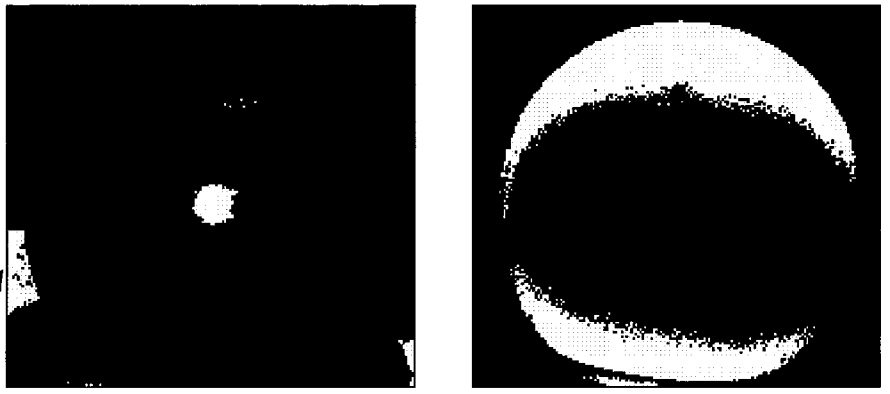
(e) DIFFUSE REFLECTION AREA (NON-POLARIZED AREA + POLARIZED AREA)

FIG. 26



(a) $\rho 2 \geqq Th\rho$

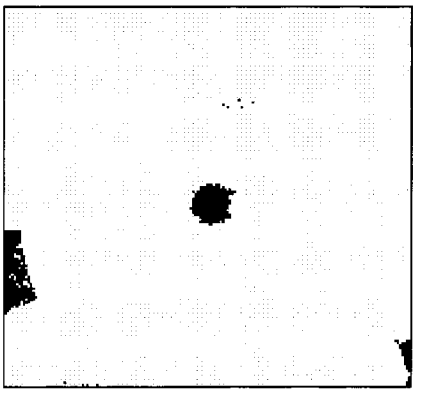
(b) DIFFUSE REFLECTION
NON-POLARIZED AREA



AREA B

(c) SPECULAR REFLECTION
POLARIZED AREA

(d) DIFFUSE REFLECTION
POLARIZED AREA



AREA B

(e) DIFFUSE REFLECTION AREA
(NON-POLARIZED AREA + POLARIZED AREA)

FIG. 27

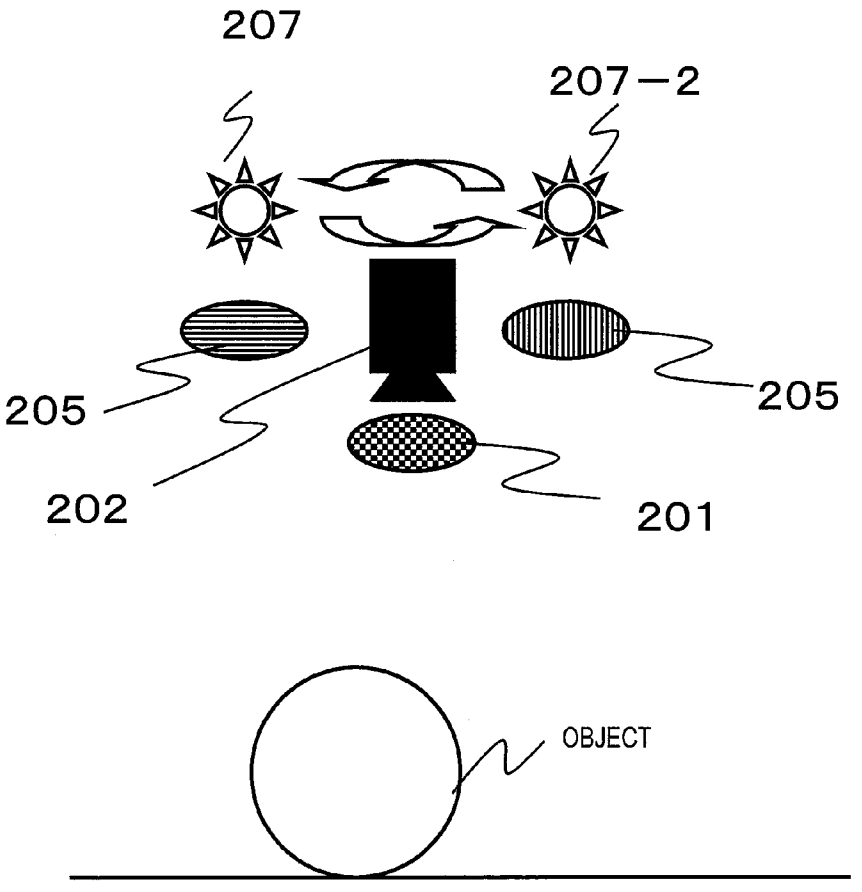


FIG. 28

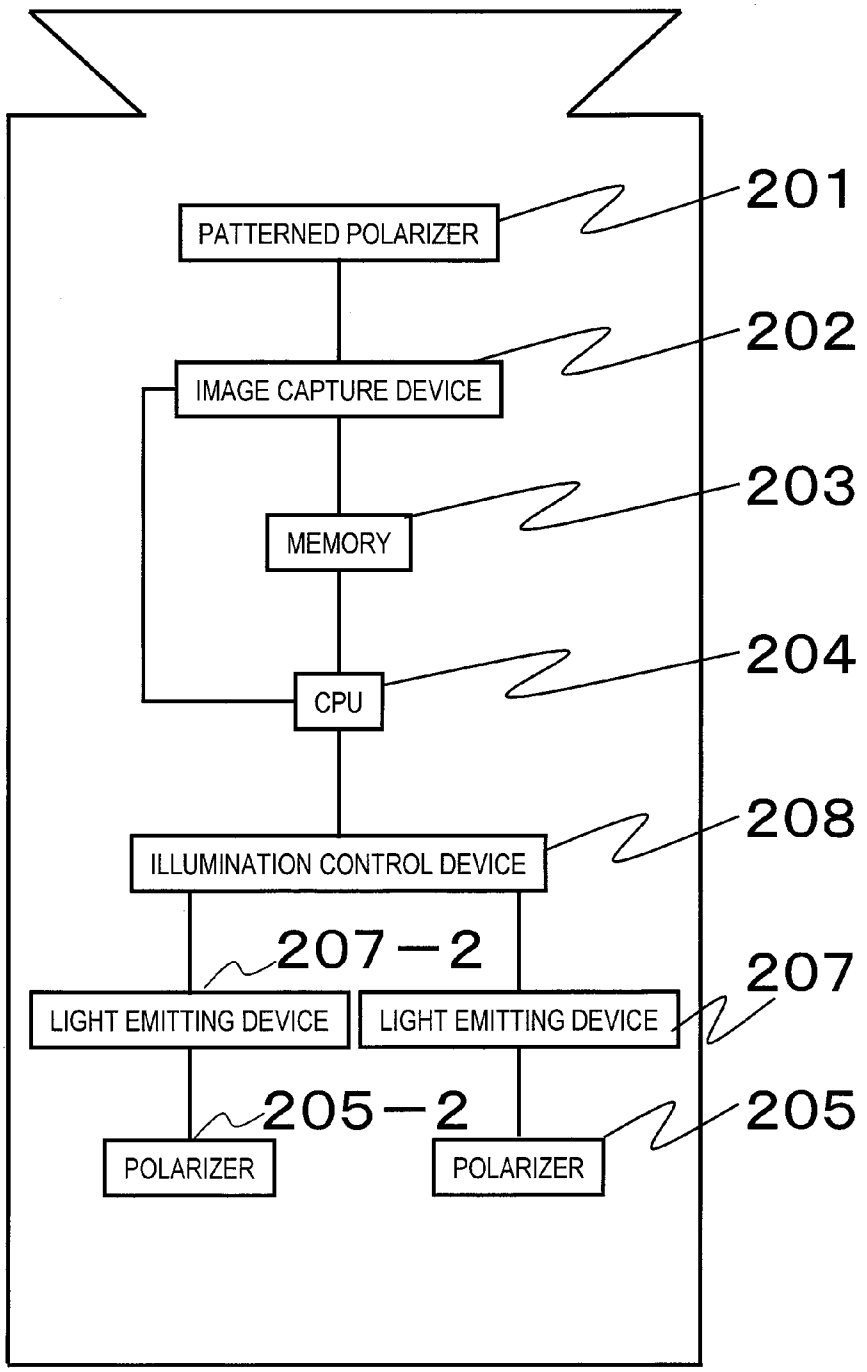

PATTERNED POLARIZER
201
IMAGE CAPTURE DEVICE
202
MEMORY
203
CPU
204
ILLUMINATION CONTROL DEVICE
208
207−2
LIGHT EMITTING DEVICE
LIGHT EMITTING DEVICE
207
205−2
POLARIZER
POLARIZER
205

FIG. 29

		LIGHT SOURCE DEPENDENCY	
		HIGH	LOW
DEGREE OF POLARIZATION	HIGH	LIGHT SOURCE -DEPENDENT POLARIZED AREA	LIGHT SOURCE -INDEPENDENT POLARIZED AREA
	LOW	LIGHT SOURCE -DEPENDENT NON-POLARIZED AREA	LIGHT SOURCE -INDEPENDENT NON-POLARIZED AREA

FIG. 30

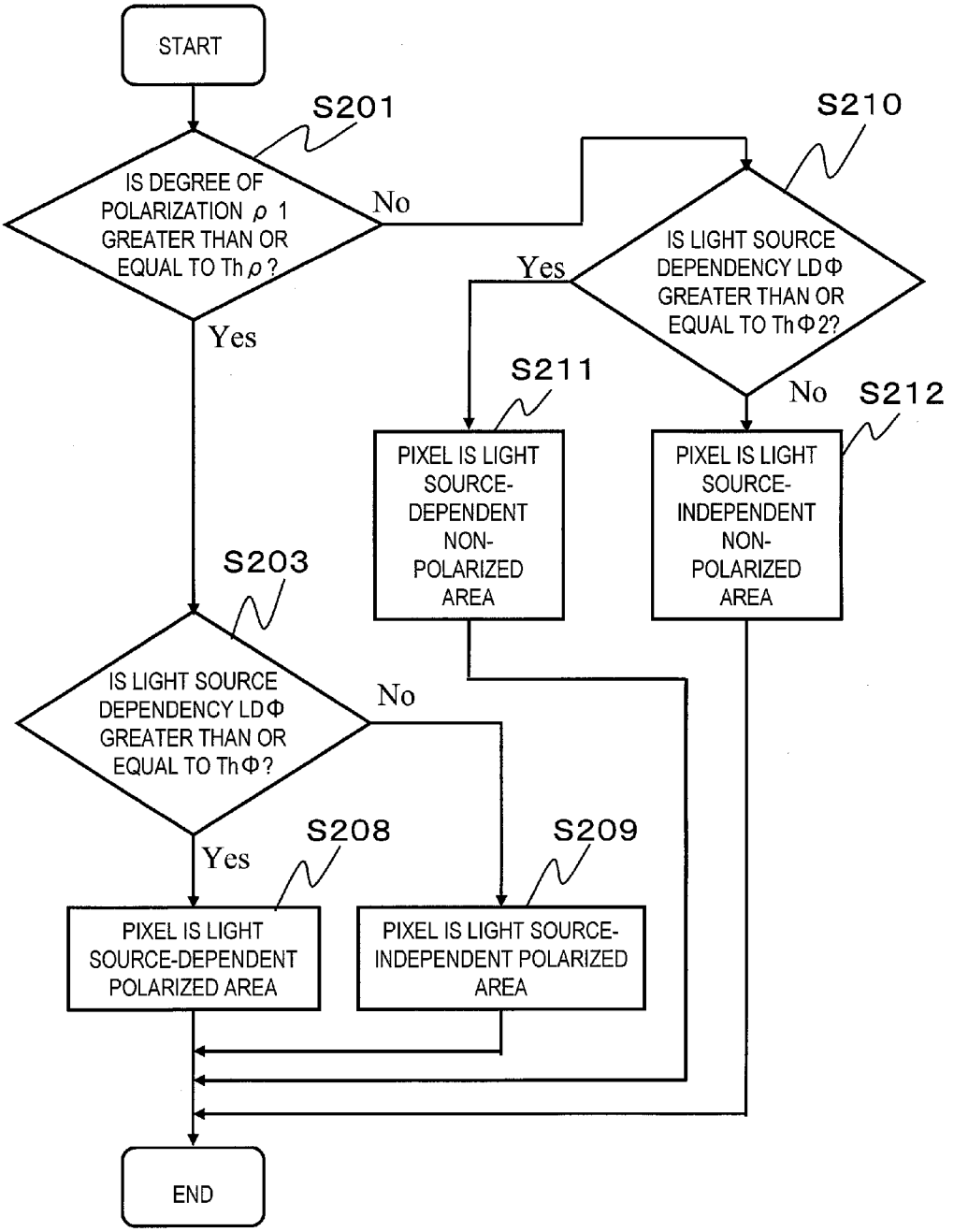

START
S201
IS DEGREE OF POLARIZATION ρ 1 GREATER THAN OR EQUAL TO Thρ?
No
Yes
S210
IS LIGHT SOURCE DEPENDENCY LDΦ GREATER THAN OR EQUAL TO ThΦ2?
Yes
No
S211
S212
PIXEL IS LIGHT SOURCE-DEPENDENT NON-POLARIZED AREA
PIXEL IS LIGHT SOURCE-INDEPENDENT NON-POLARIZED AREA
S203
IS LIGHT SOURCE DEPENDENCY LDΦ GREATER THAN OR EQUAL TO ThΦ?
No
Yes
S208
S209
PIXEL IS LIGHT SOURCE-DEPENDENT POLARIZED AREA
PIXEL IS LIGHT SOURCE-INDEPENDENT POLARIZED AREA
END

FIG. 31

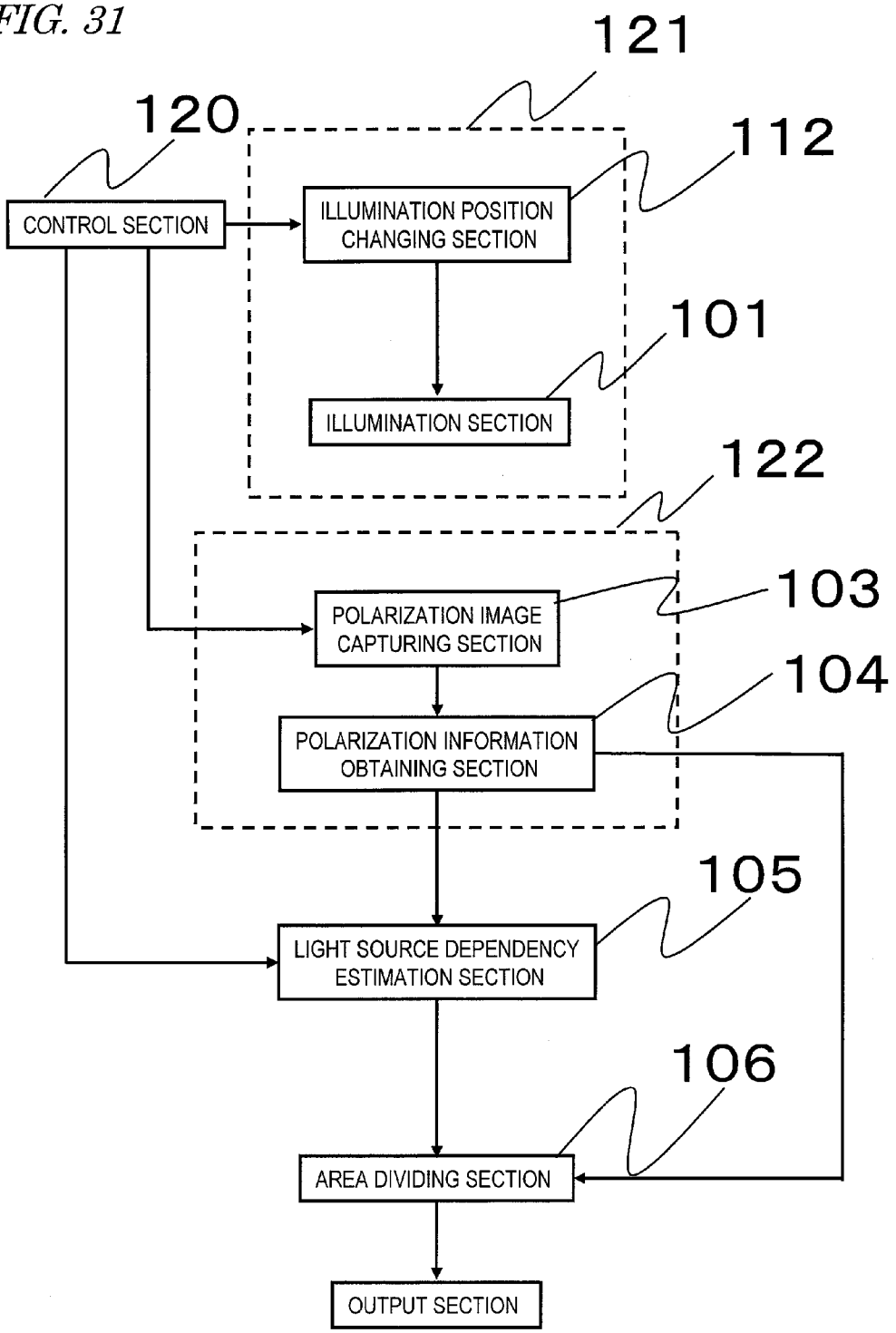

121
120
112
CONTROL SECTION
ILLUMINATION POSITION CHANGING SECTION
101
ILLUMINATION SECTION
122
103
POLARIZATION IMAGE CAPTURING SECTION
104
POLARIZATION INFORMATION OBTAINING SECTION
105
LIGHT SOURCE DEPENDENCY ESTIMATION SECTION
106
AREA DIVIDING SECTION
OUTPUT SECTION

FIG. 32

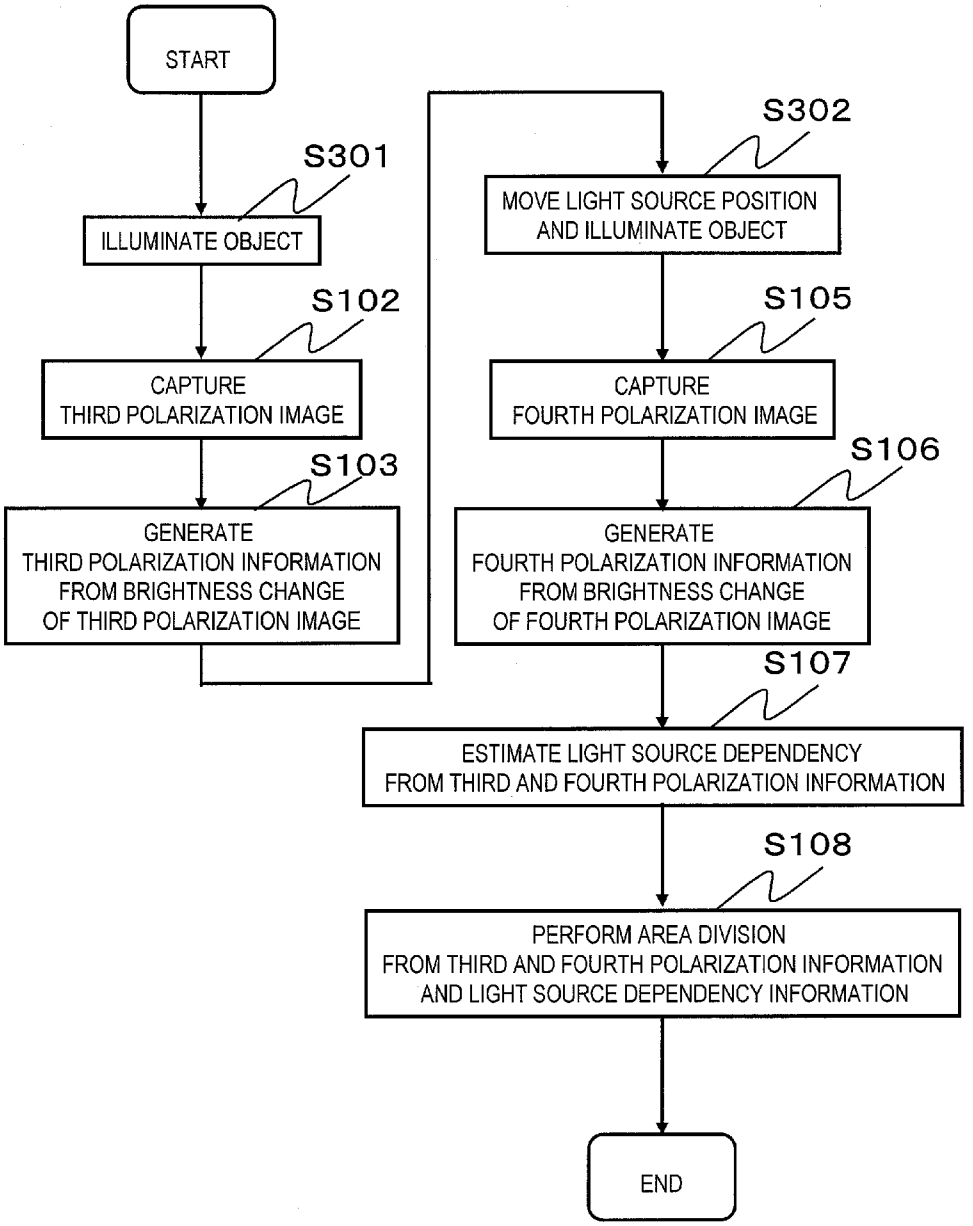

START
S301
ILLUMINATE OBJECT
S102
CAPTURE
THIRD POLARIZATION IMAGE
S103
GENERATE
THIRD POLARIZATION INFORMATION
FROM BRIGHTNESS CHANGE
OF THIRD POLARIZATION IMAGE
S302
MOVE LIGHT SOURCE POSITION
AND ILLUMINATE OBJECT
S105
CAPTURE
FOURTH POLARIZATION IMAGE
S106
GENERATE
FOURTH POLARIZATION INFORMATION
FROM BRIGHTNESS CHANGE
OF FOURTH POLARIZATION IMAGE
S107
ESTIMATE LIGHT SOURCE DEPENDENCY
FROM THIRD AND FOURTH POLARIZATION INFORMATION
S108
PERFORM AREA DIVISION
FROM THIRD AND FOURTH POLARIZATION INFORMATION
AND LIGHT SOURCE DEPENDENCY INFORMATION
END

FIG. 33

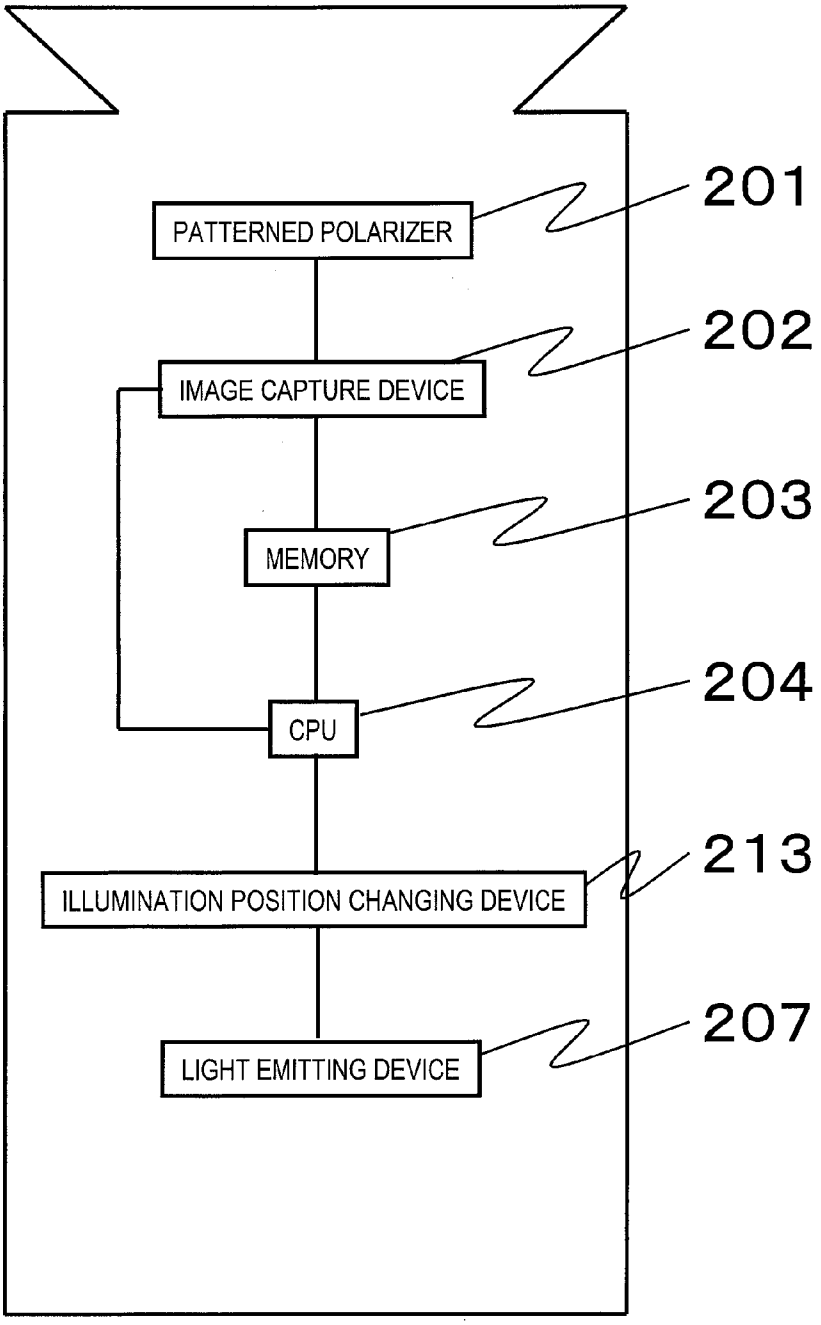

PATTERNED POLARIZER
201
IMAGE CAPTURE DEVICE
202
MEMORY
203
CPU
204
ILLUMINATION POSITION CHANGING DEVICE
213
LIGHT EMITTING DEVICE
207

FIG. 34

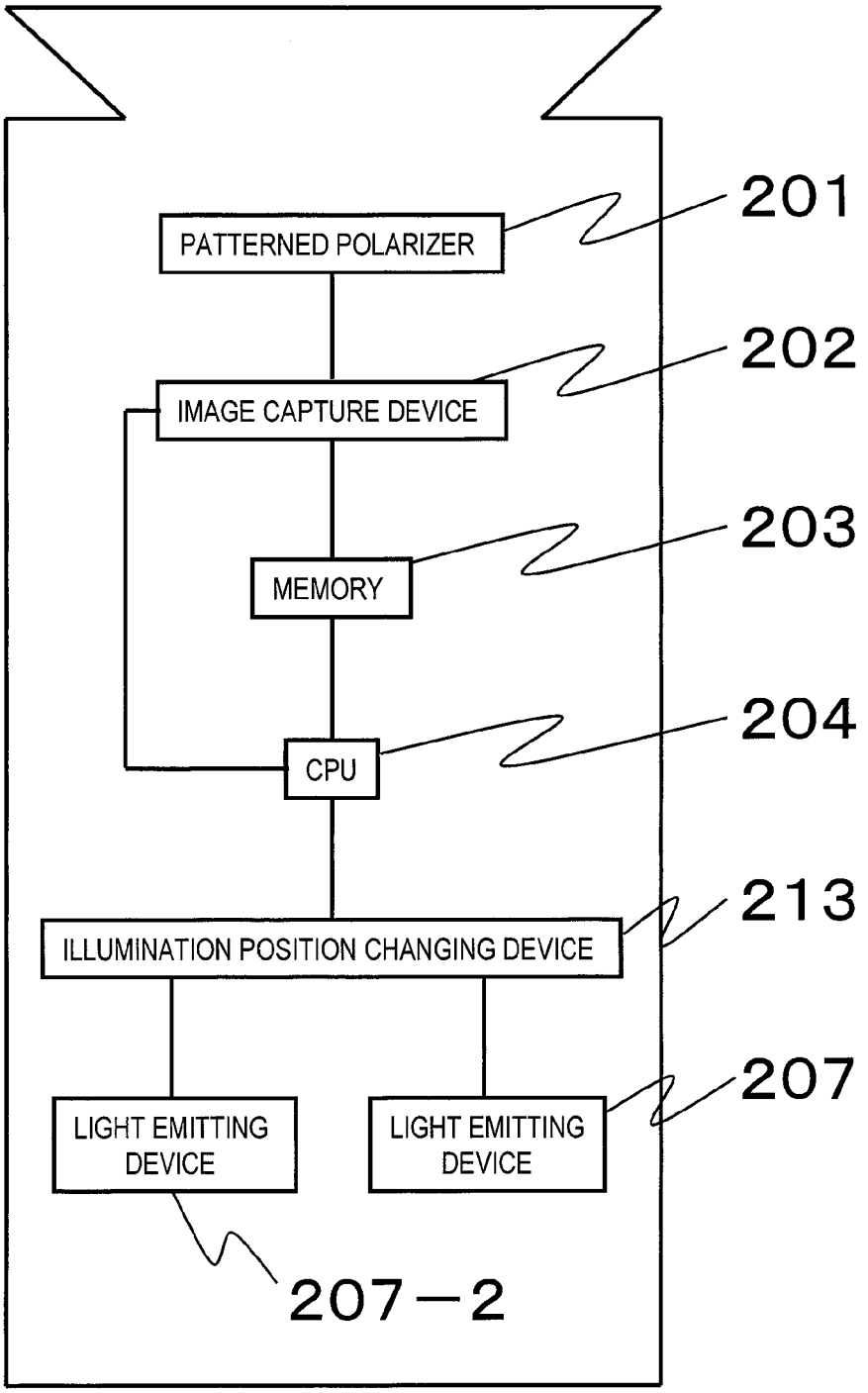

PATTERNED POLARIZER
201
IMAGE CAPTURE DEVICE
202
MEMORY
203
CPU
204
ILLUMINATION POSITION CHANGING DEVICE
213
LIGHT EMITTING DEVICE
LIGHT EMITTING DEVICE
207
207-2

FIG. 35

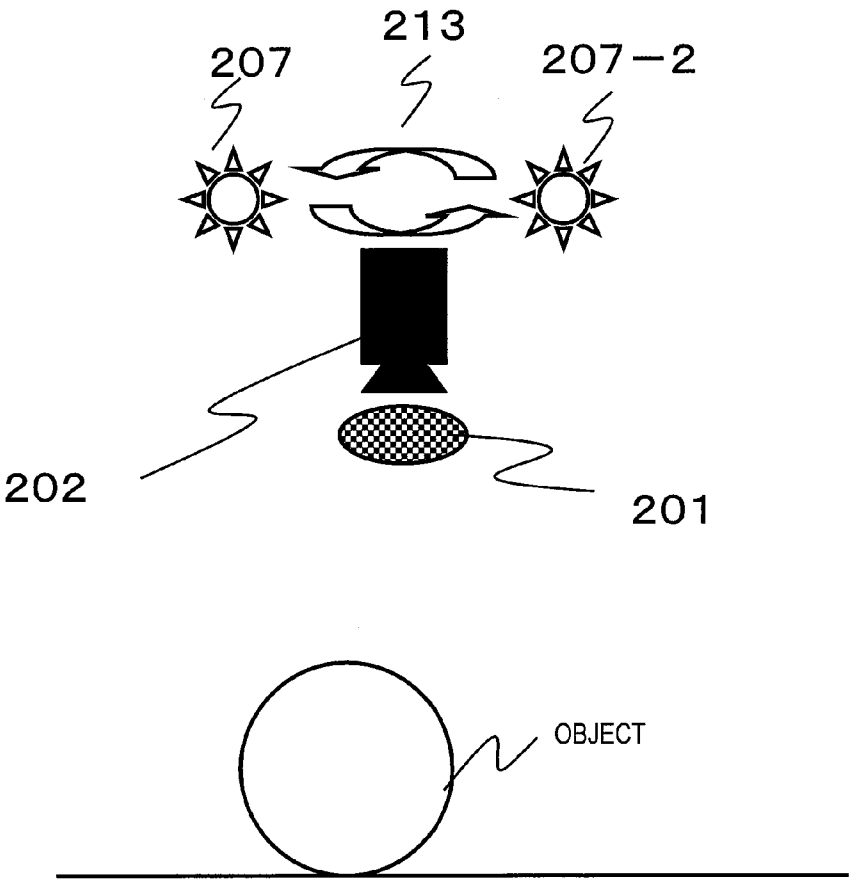


FIG. 36

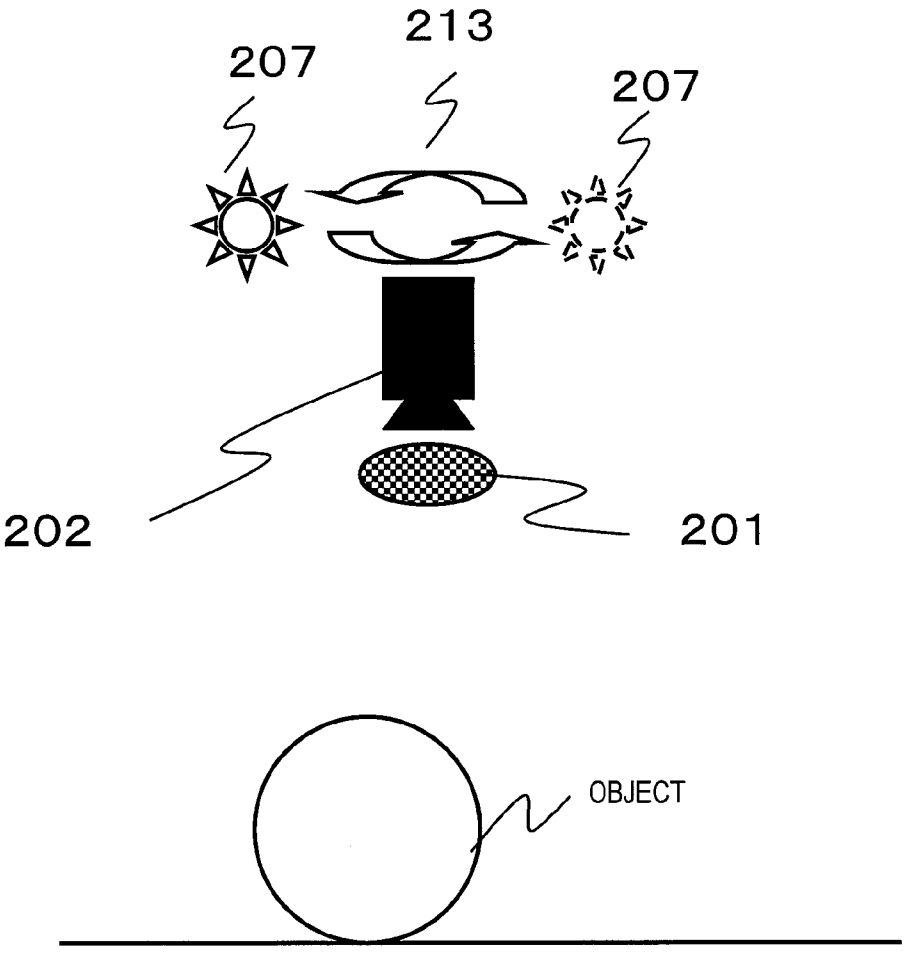
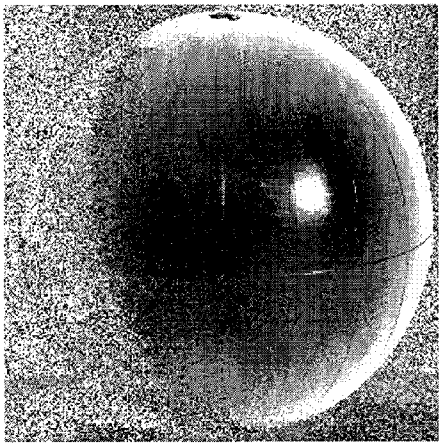
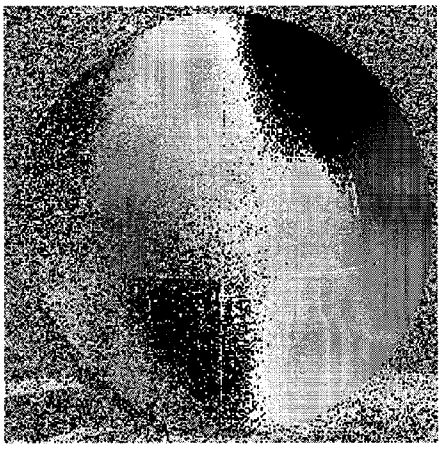


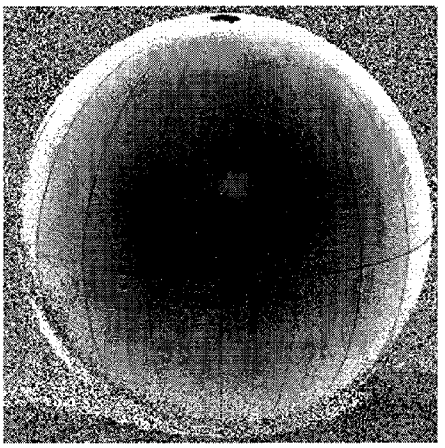
FIG. 37



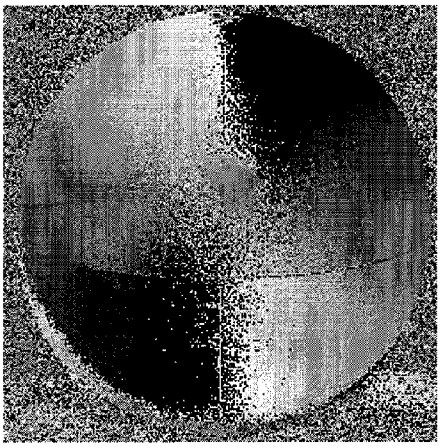
(a) $\rho 3$
(LIGHT SOURCE TOWARD RIGHT SIDE)



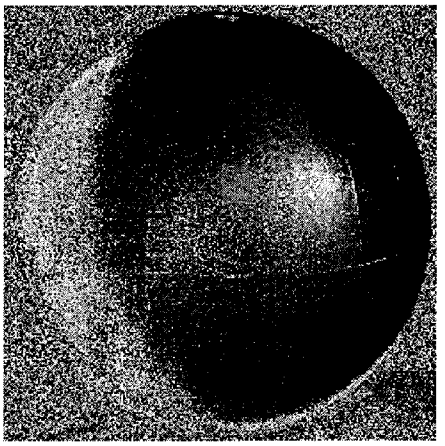
(b) ϕ max3
(LIGHT SOURCE TOWARD RIGHT SIDE)



(c) $\rho 4$
(LIGHT SOURCE TOWARD UPPER SIDE)



(d) ϕ max4
(LIGHT SOURCE TOWARD UPPER SIDE)



(e) LD ϕ

FIG. 38

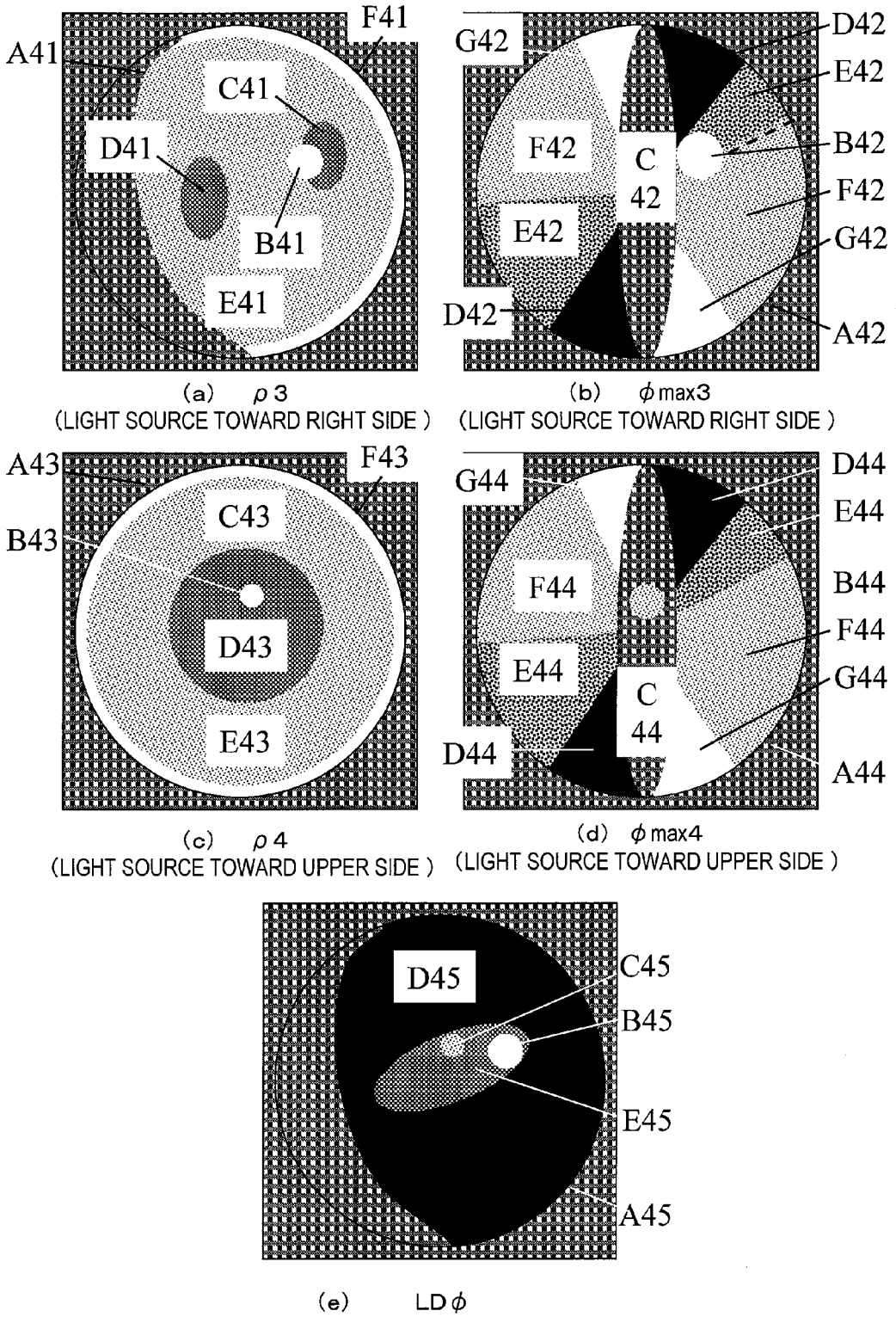

A41
F41
C41
D41
B41
E41
(a) ρ3
(LIGHT SOURCE TOWARD RIGHT SIDE)
G42
D42
E42
F42
C
42
B42
F42
E42
G42
D42
A42
(b) φmax3
(LIGHT SOURCE TOWARD RIGHT SIDE)
A43
F43
B43
C43
D43
E43
(c) ρ4
(LIGHT SOURCE TOWARD UPPER SIDE)
G44
D44
E44
F44
B44
F44
E44
C
44
G44
D44
A44
(d) φmax4
(LIGHT SOURCE TOWARD UPPER SIDE)
D45
C45
B45
E45
A45
(e) LDφ

FIG. 39

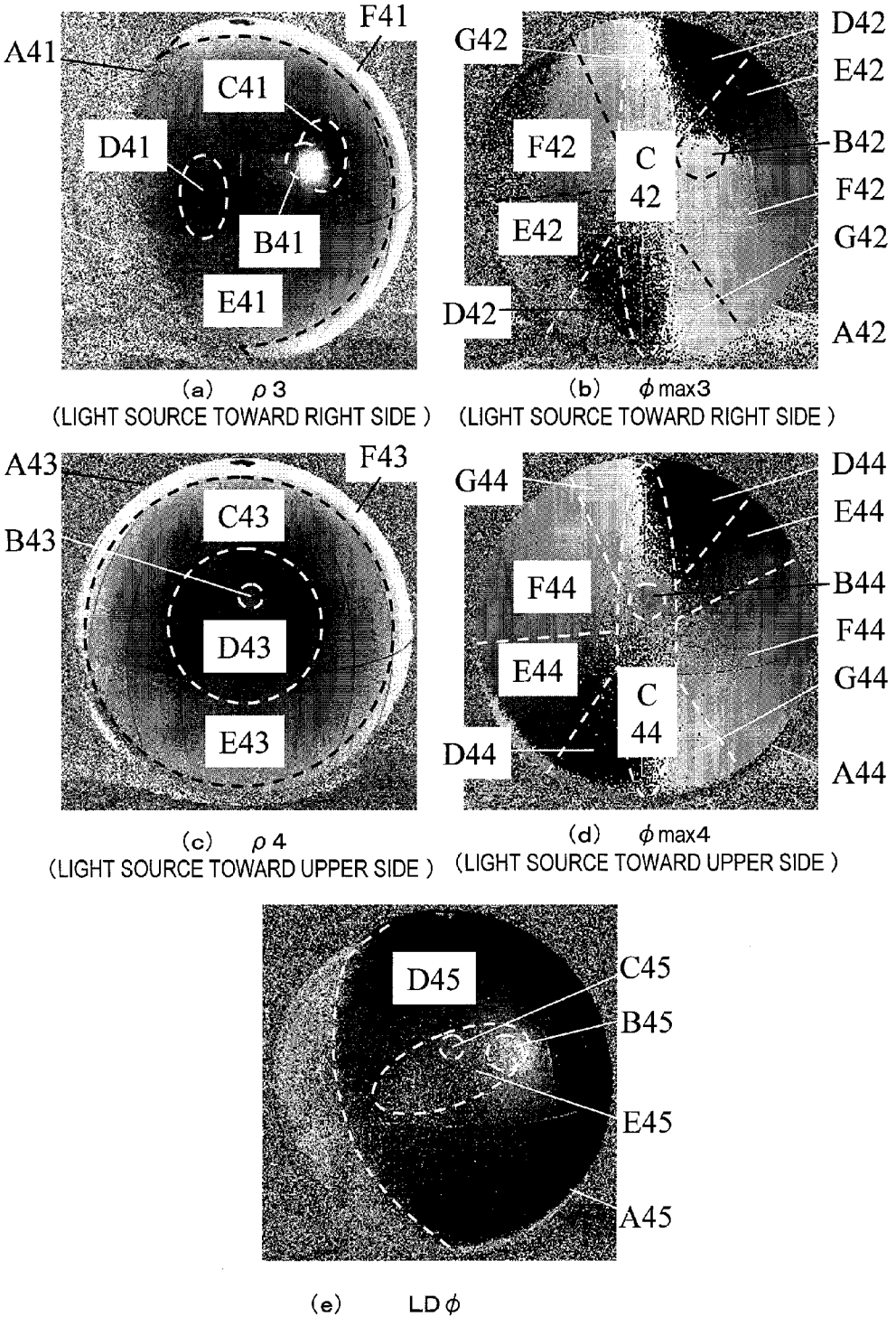

A41
F41
C41
D41
B41
E41
(a) ρ3
(LIGHT SOURCE TOWARD RIGHT SIDE)
G42
D42
E42
B42
F42
C
42
F42
E42
G42
D42
A42
(b) φmax3
(LIGHT SOURCE TOWARD RIGHT SIDE)
A43
F43
B43
C43
D43
E43
(c) ρ4
(LIGHT SOURCE TOWARD UPPER SIDE)
G44
D44
E44
B44
F44
F44
E44
G44
C
44
D44
A44
(d) φmax4
(LIGHT SOURCE TOWARD UPPER SIDE)
D45
C45
B45
E45
A45
(e) LDφ

FIG. 40

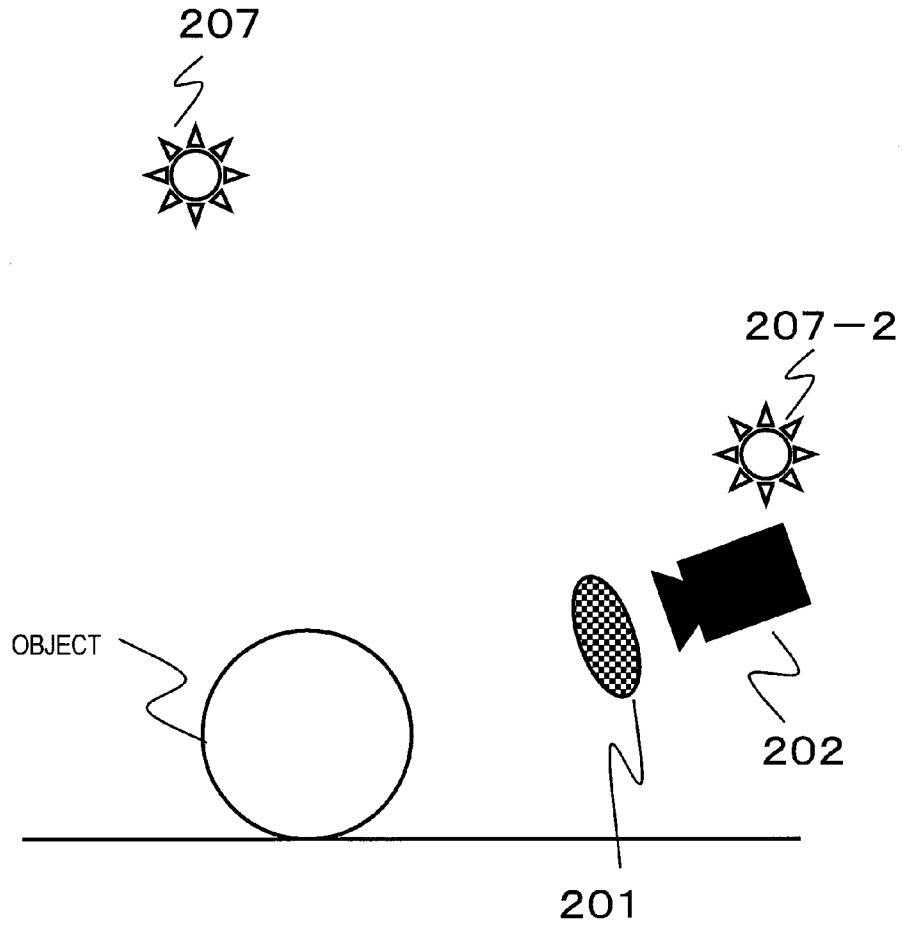
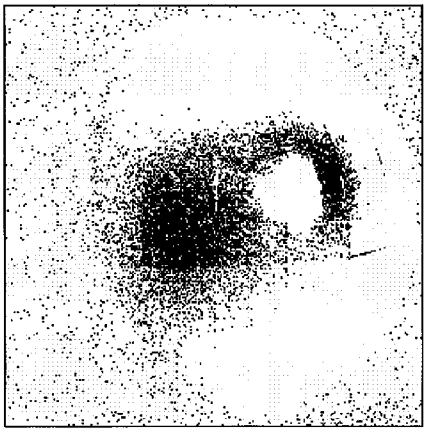
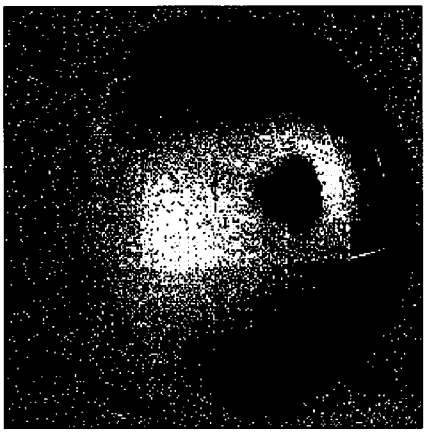


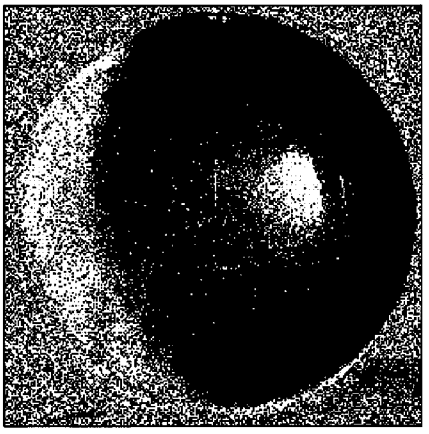
FIG. 41



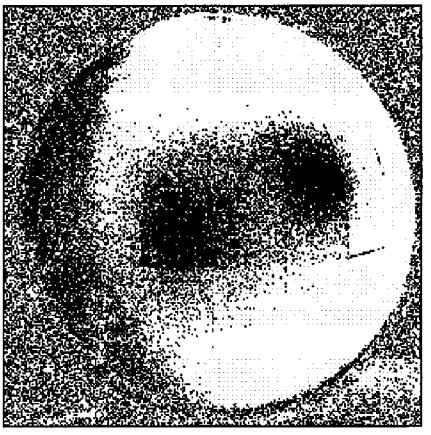
(a) $\rho 3 \geqq Th\rho$



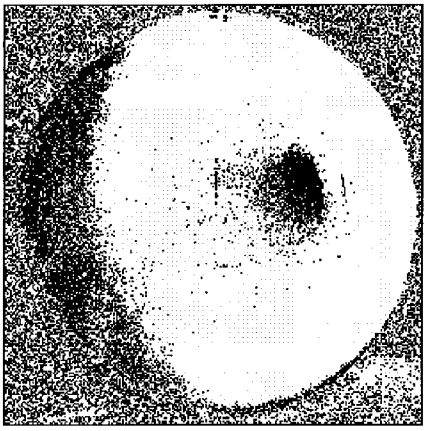
(b) DIFFUSE REFLECTION NON-POLARIZED AREA



(c) SPECULAR REFLECTION POLARIZED AREA

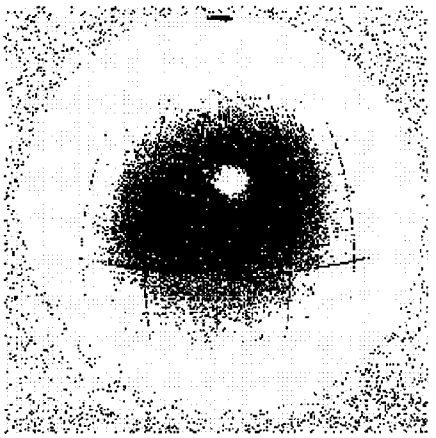


(d) DIFFUSE REFLECTION POLARIZED AREA

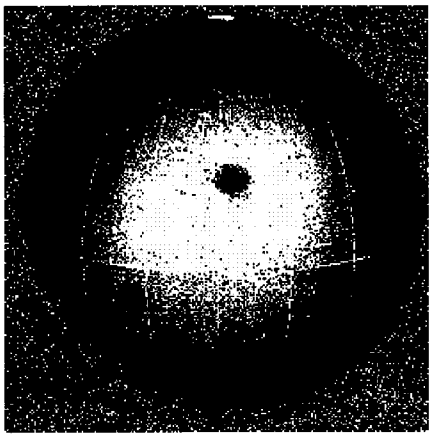


(e) DIFFUSE REFLECTION AREA (NON-POLARIZED AREA + POLARIZED AREA)

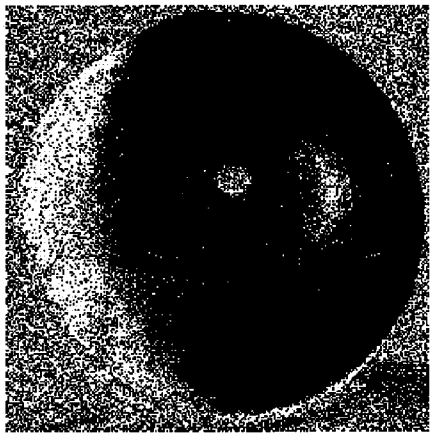
FIG. 42



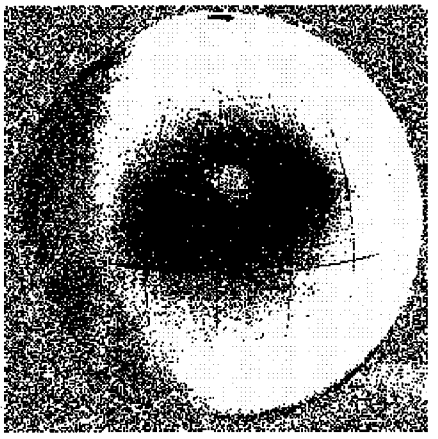
(a) $\rho 4 \geqq Th\rho$



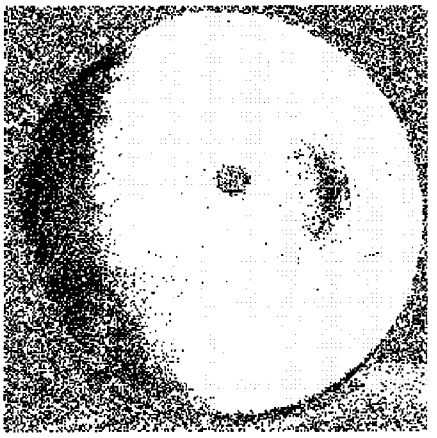
(b) DIFFUSE REFLECTION NON-POLARIZED AREA



(c) SPECULAR REFLECTION POLARIZED AREA



(d) DIFFUSE REFLECTION POLARIZED AREA



(e) DIFFUSE REFLECTION AREA (NON-POLARIZED AREA + POLARIZED AREA))

FIG. 43

<table>
<tr><td colspan="4" rowspan="2"></td><td colspan="2">LIGHT SOURCE DEPENDENCY</td></tr>
<tr><td>HIGH</td><td>LOW</td></tr>
<tr><td rowspan="3">BRIGHTNESS</td><td rowspan="2">HIGH</td><td rowspan="2">DEGREE OF POLARIZATION</td><td>HIGH</td><td>LIGHT SOURCE -DEPENDENT POLARIZED AREA</td><td>LIGHT SOURCE -INDEPENDENT POLARIZED AREA</td></tr>
<tr><td>LOW</td><td>LIGHT SOURCE -DEPENDENT NON-POLARIZED AREA</td><td>LIGHT SOURCE -INDEPENDENT NON-POLARIZED AREA</td></tr>
<tr><td>LOW</td><td colspan="3">SHADED AREA</td></tr>
</table>

FIG. 44

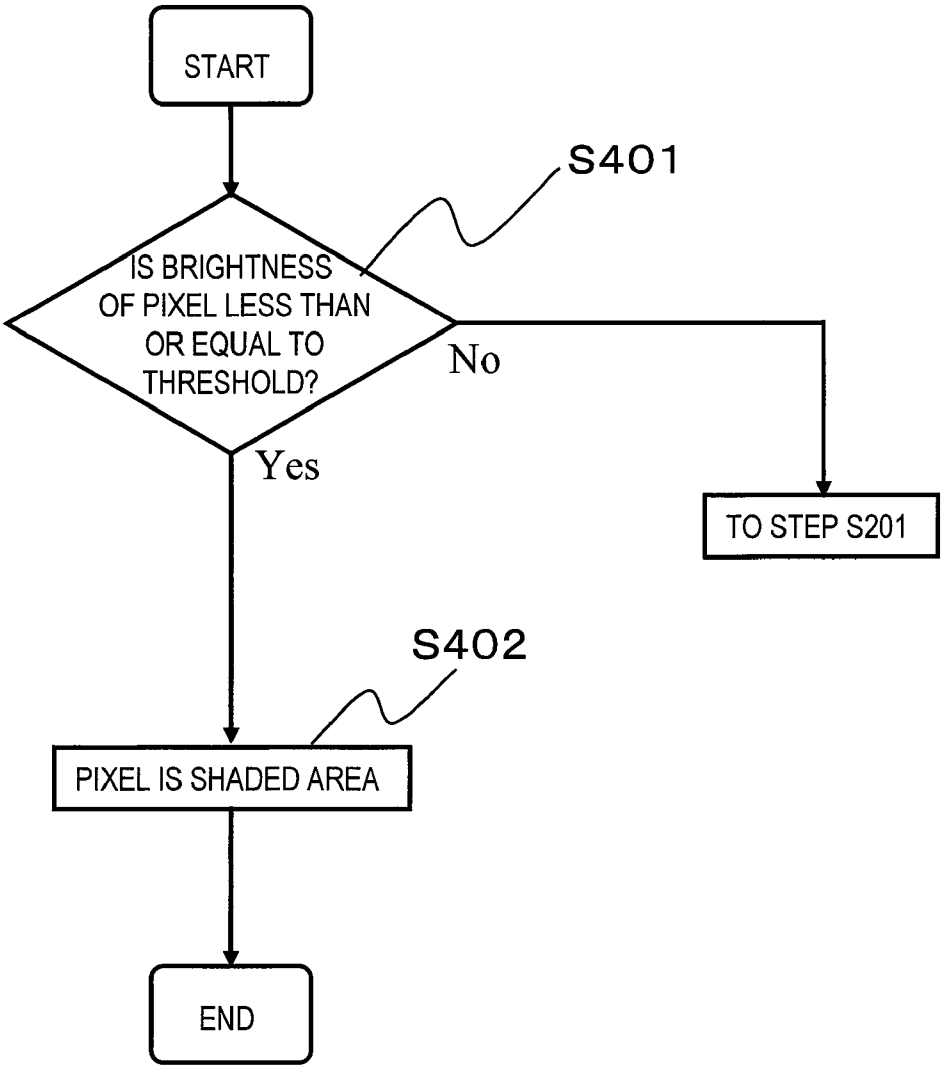

START
S401
IS BRIGHTNESS OF PIXEL LESS THAN OR EQUAL TO THRESHOLD?
No
Yes
TO STEP S201
S402
PIXEL IS SHADED AREA
END

FIG. 45

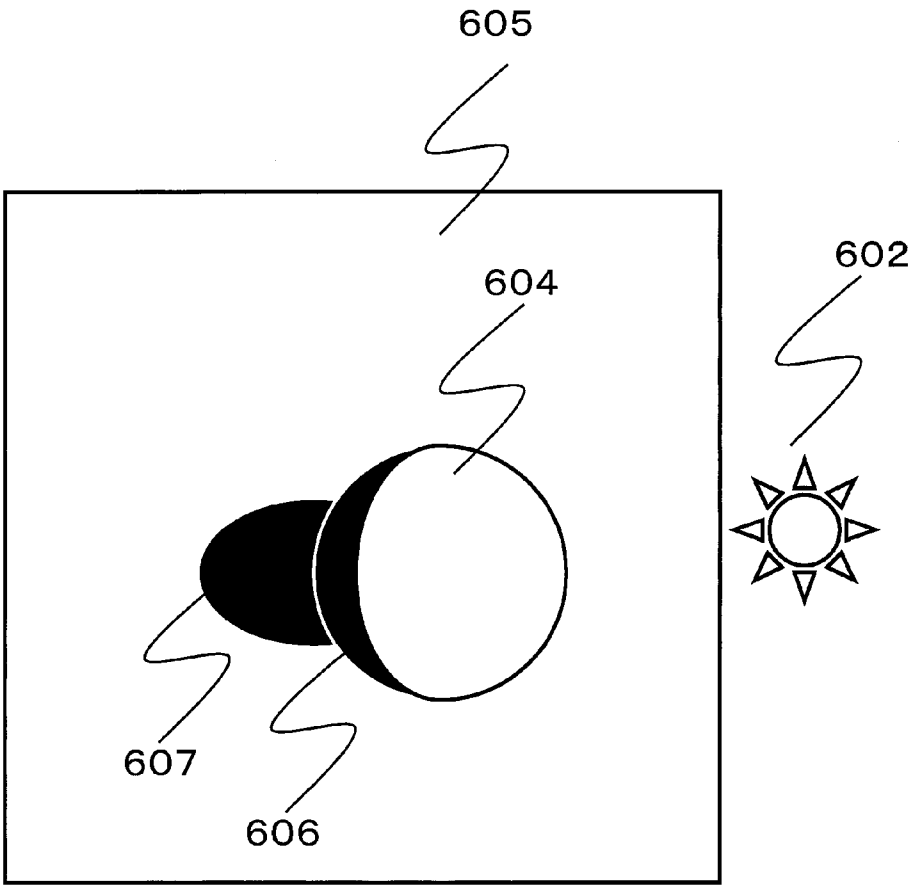


FIG. 46

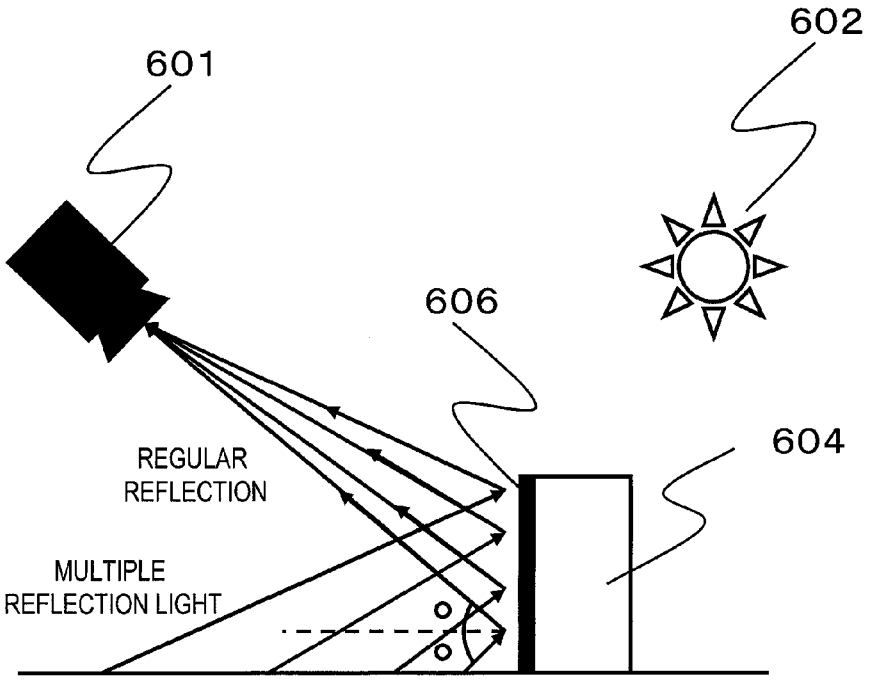

601
602
606
604
REGULAR
REFLECTION
MULTIPLE
REFLECTION LIGHT

FIG. 47

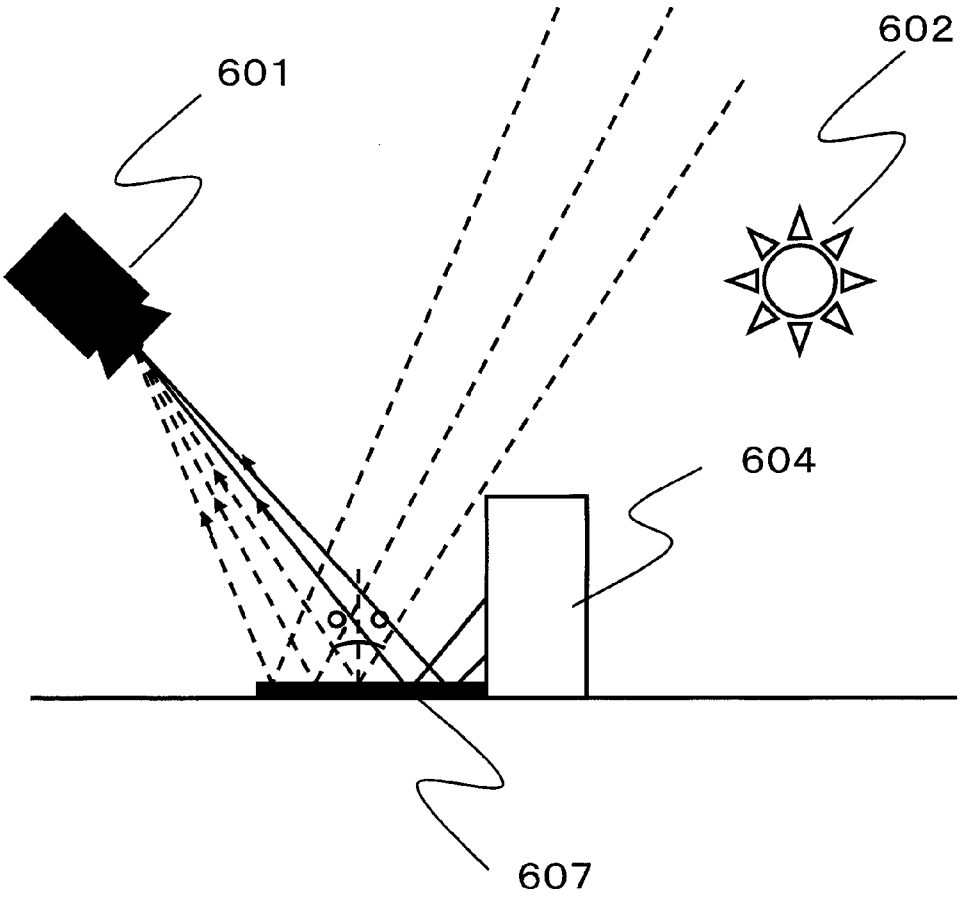


FIG. 48

				LIGHT SOURCE DEPENDENCY	
				HIGH	LOW
BRIGHTNESS	HIGH	DEGREE OF POLARIZATION	HIGH	LIGHT SOURCE -DEPENDENT POLARIZED AREA	LIGHT SOURCE -INDEPENDENT POLARIZED AREA
			LOW	LIGHT SOURCE -DEPENDENT NON-POLARIZED AREA	LIGHT SOURCE -DEPENDENT NON-POLARIZED AREA
	LOW	POLARIZATION ERROR	LARGE	cast shadow	
			SMALL	attached shadow	

FIG. 49

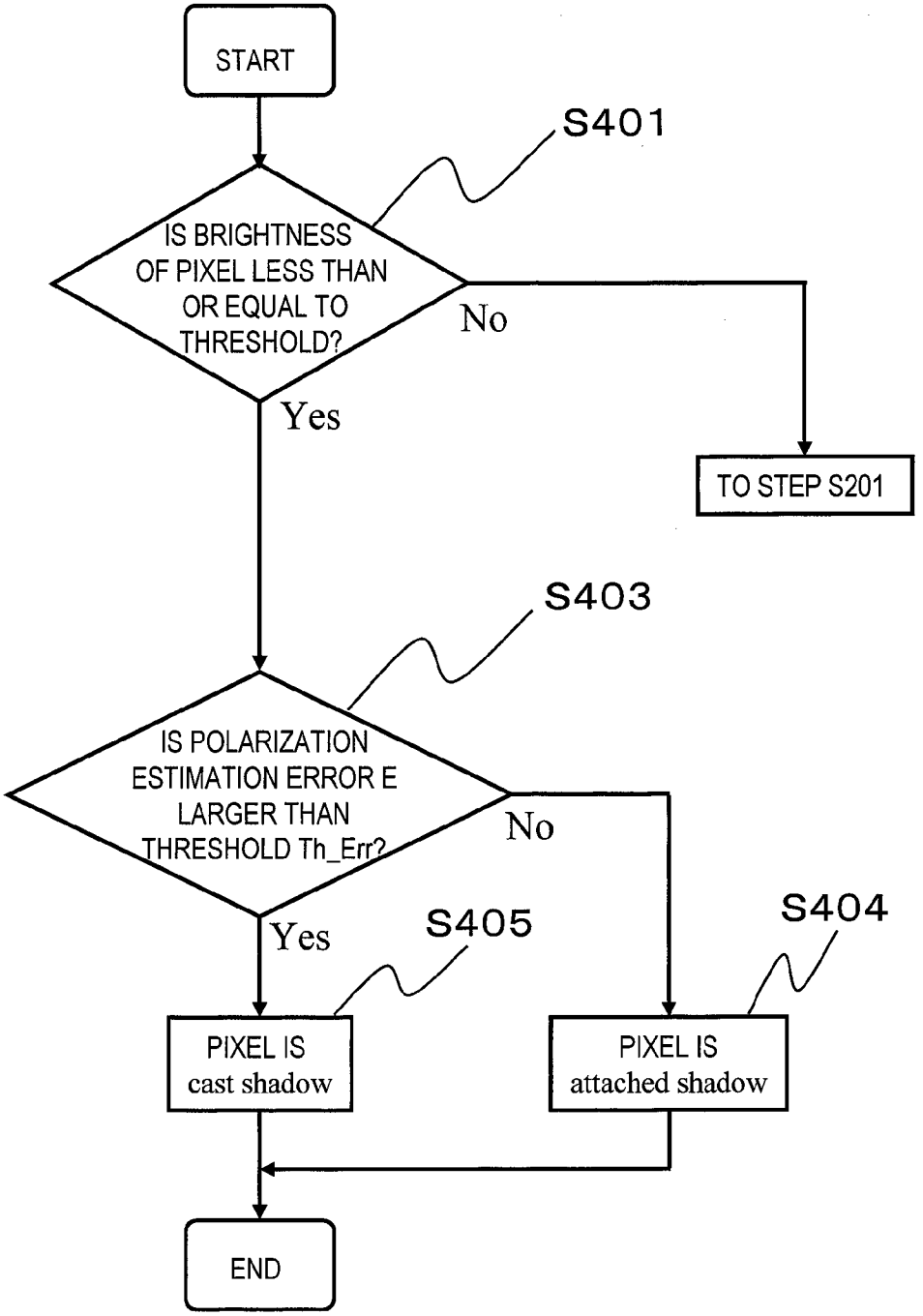

START
S401
IS BRIGHTNESS OF PIXEL LESS THAN OR EQUAL TO THRESHOLD?
No
Yes
TO STEP S201
S403
IS POLARIZATION ESTIMATION ERROR E LARGER THAN THRESHOLD Th_Err?
No
Yes
S405
S404
PIXEL IS cast shadow
PIXEL IS attached shadow
END

FIG. 50

<table>
<tr><td colspan="4" rowspan="2"></td><td colspan="2">LIGHT SOURCE DEPENDENCY</td></tr>
<tr><td>HIGH</td><td>LOW</td></tr>
<tr><td rowspan="4">BRIGHTNESS</td><td rowspan="2">HIGH</td><td rowspan="2">DEGREE OF POLARIZATION</td><td>HIGH</td><td>LIGHT SOURCE -DEPENDENT POLARIZED AREA</td><td>LIGHT SOURCE -INDEPENDENT POLARIZED AREA</td></tr>
<tr><td>LOW</td><td>LIGHT SOURCE -DEPENDENT NON-POLARIZED AREA</td><td>LIGHT SOURCE -DEPENDENT NON-POLARIZED AREA</td></tr>
<tr><td rowspan="2">LOW</td><td rowspan="2">DEGREE OF POLARIZATION</td><td>HIGH</td><td colspan="2">attached shadow</td></tr>
<tr><td>LOW</td><td colspan="2">cast shadow</td></tr>
</table>

FIG. 51

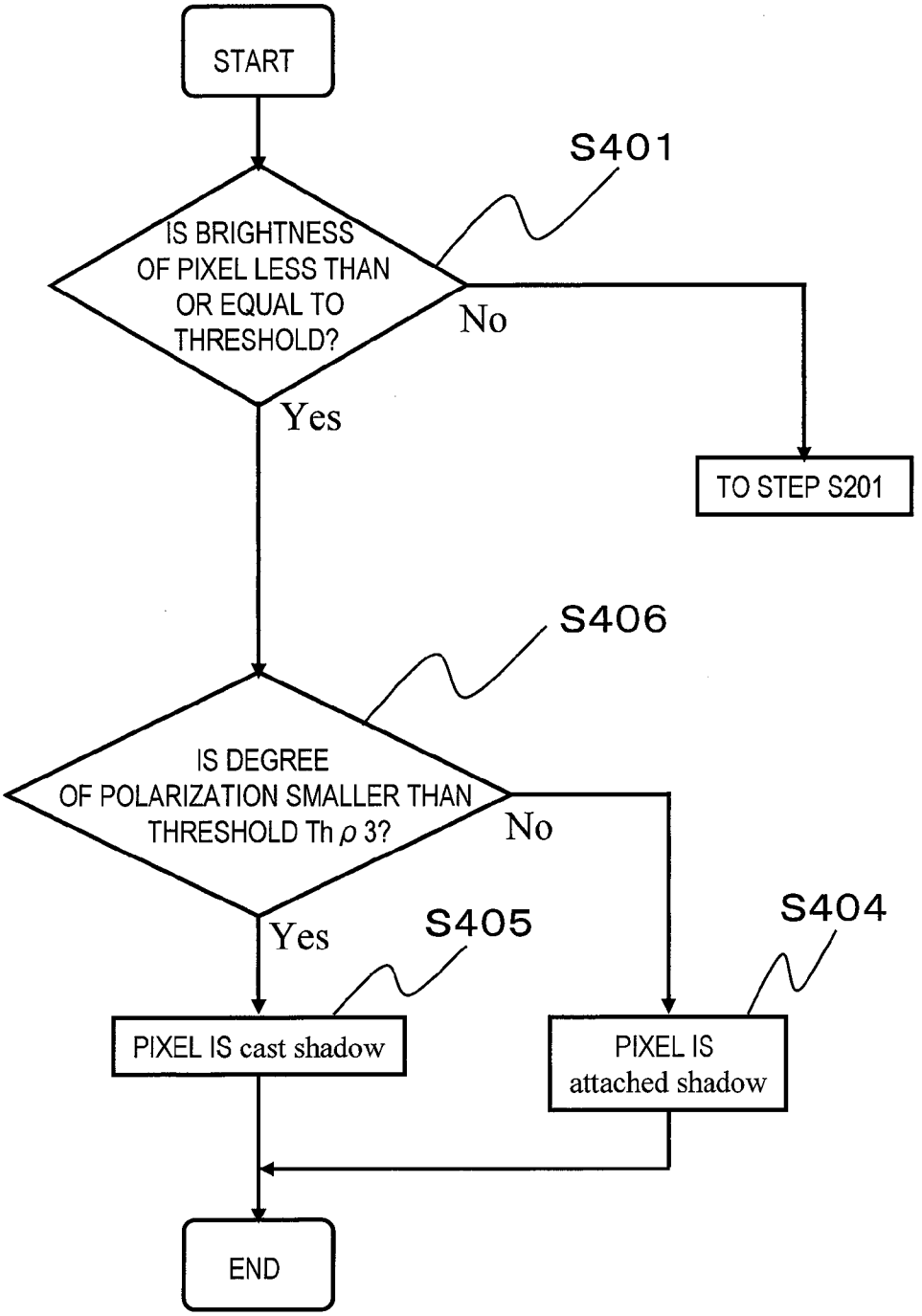

START
S401
IS BRIGHTNESS OF PIXEL LESS THAN OR EQUAL TO THRESHOLD?
No
Yes
TO STEP S201
S406
IS DEGREE OF POLARIZATION SMALLER THAN THRESHOLD Th ρ 3?
No
Yes
S405
S404
PIXEL IS cast shadow
PIXEL IS attached shadow
END

FIG. 52

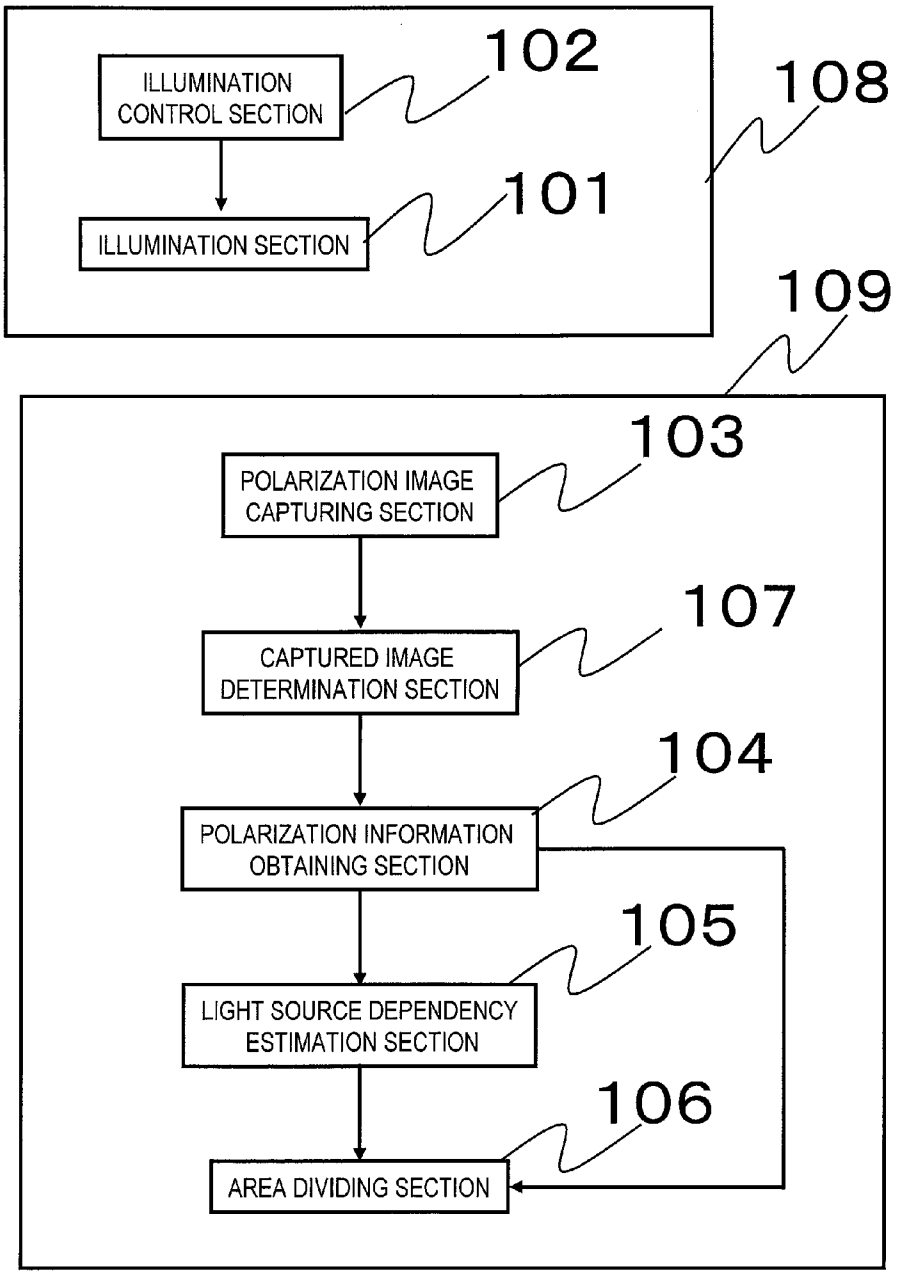

ILLUMINATION CONTROL SECTION
102
108
ILLUMINATION SECTION
101
109
103
POLARIZATION IMAGE CAPTURING SECTION
107
CAPTURED IMAGE DETERMINATION SECTION
104
POLARIZATION INFORMATION OBTAINING SECTION
105
LIGHT SOURCE DEPENDENCY ESTIMATION SECTION
106
AREA DIVIDING SECTION

FIG. 53

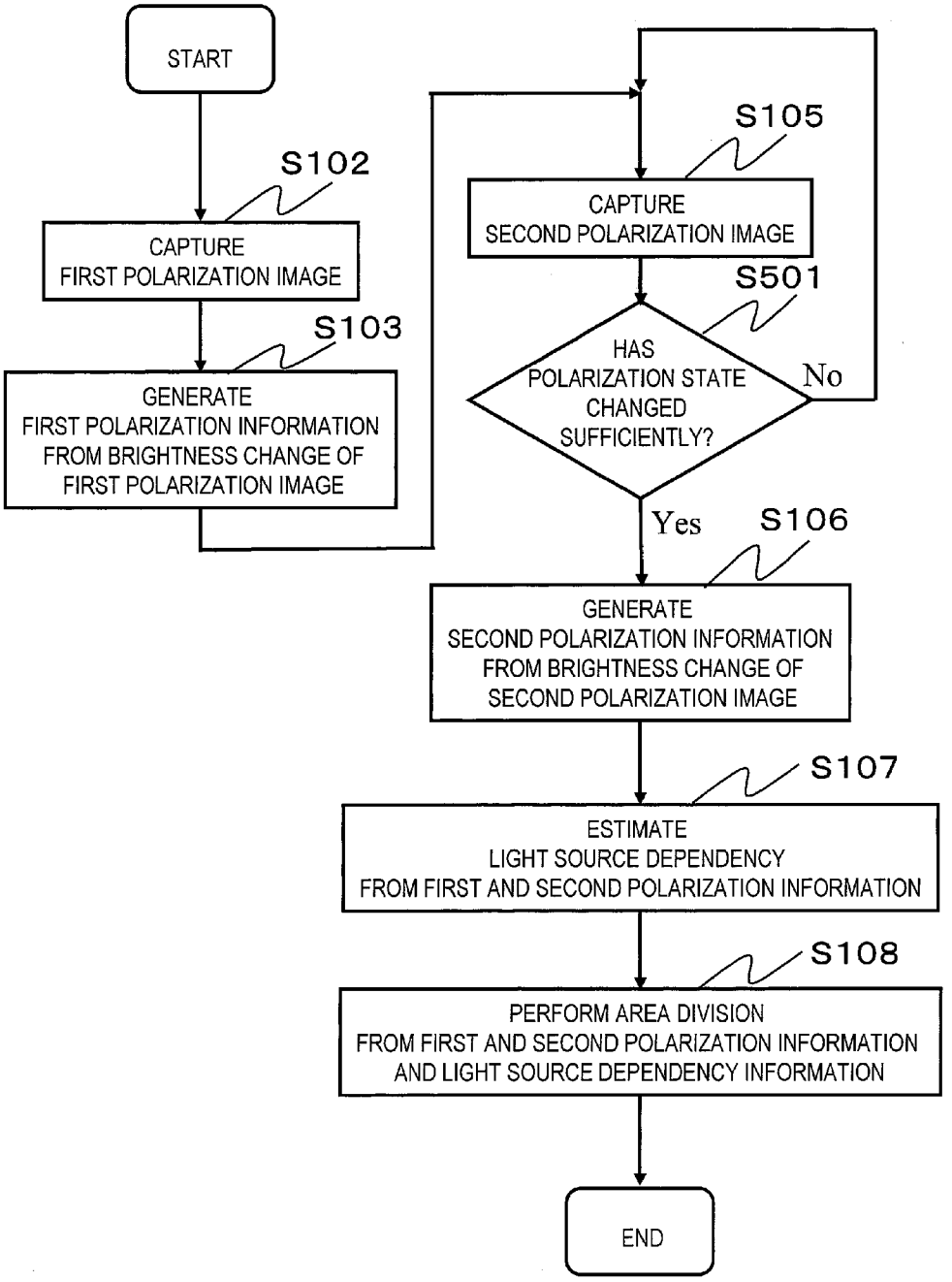

START
S102
CAPTURE FIRST POLARIZATION IMAGE
S103
GENERATE FIRST POLARIZATION INFORMATION FROM BRIGHTNESS CHANGE OF FIRST POLARIZATION IMAGE
S105
CAPTURE SECOND POLARIZATION IMAGE
S501
HAS POLARIZATION STATE CHANGED SUFFICIENTLY?
No
Yes
S106
GENERATE SECOND POLARIZATION INFORMATION FROM BRIGHTNESS CHANGE OF SECOND POLARIZATION IMAGE
S107
ESTIMATE LIGHT SOURCE DEPENDENCY FROM FIRST AND SECOND POLARIZATION INFORMATION
S108
PERFORM AREA DIVISION FROM FIRST AND SECOND POLARIZATION INFORMATION AND LIGHT SOURCE DEPENDENCY INFORMATION
END

FIG. 54

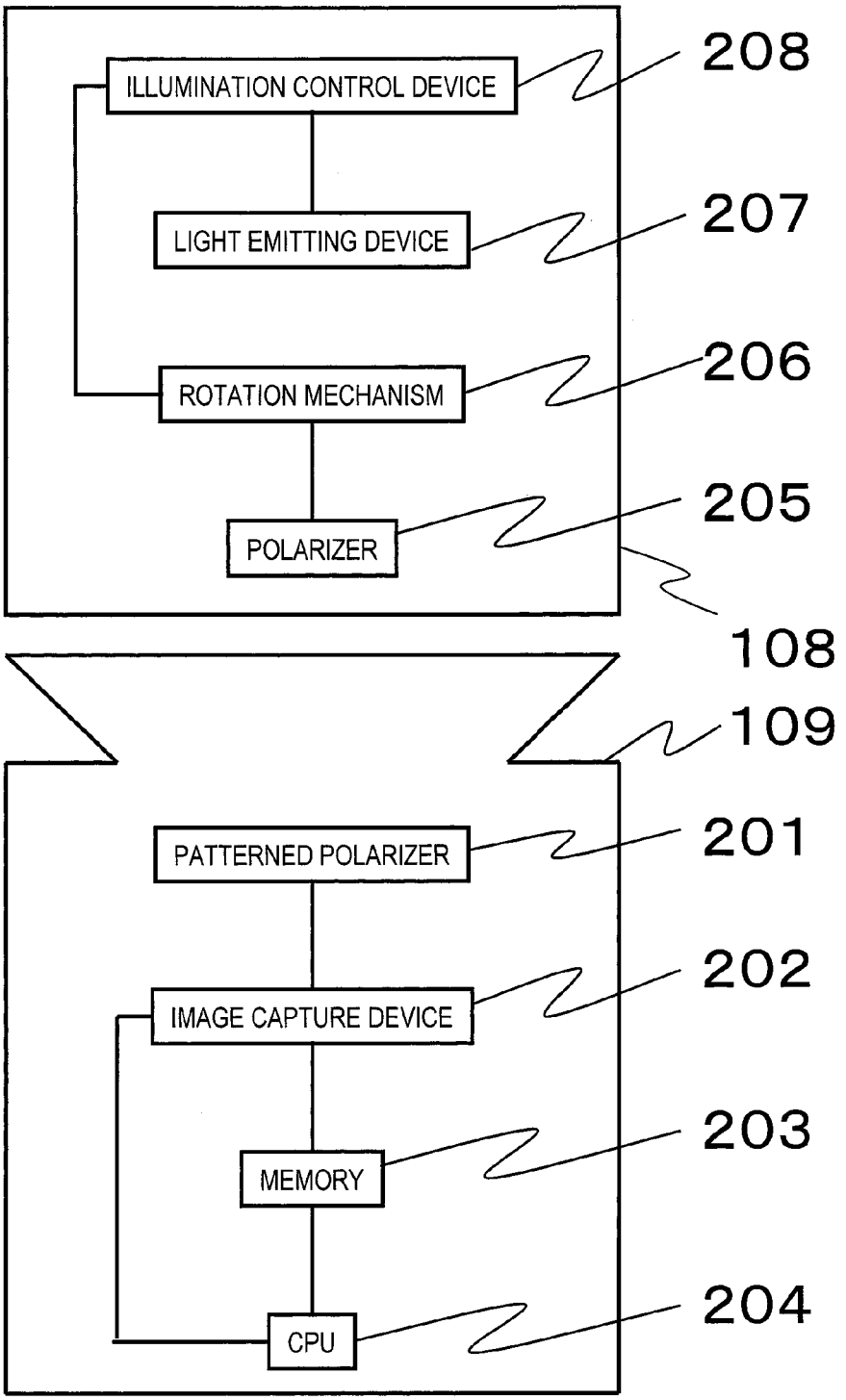

ILLUMINATION CONTROL DEVICE
208
LIGHT EMITTING DEVICE
207
ROTATION MECHANISM
206
POLARIZER
205
108
109
PATTERNED POLARIZER
201
IMAGE CAPTURE DEVICE
202
MEMORY
203
CPU
204

FIG. 55

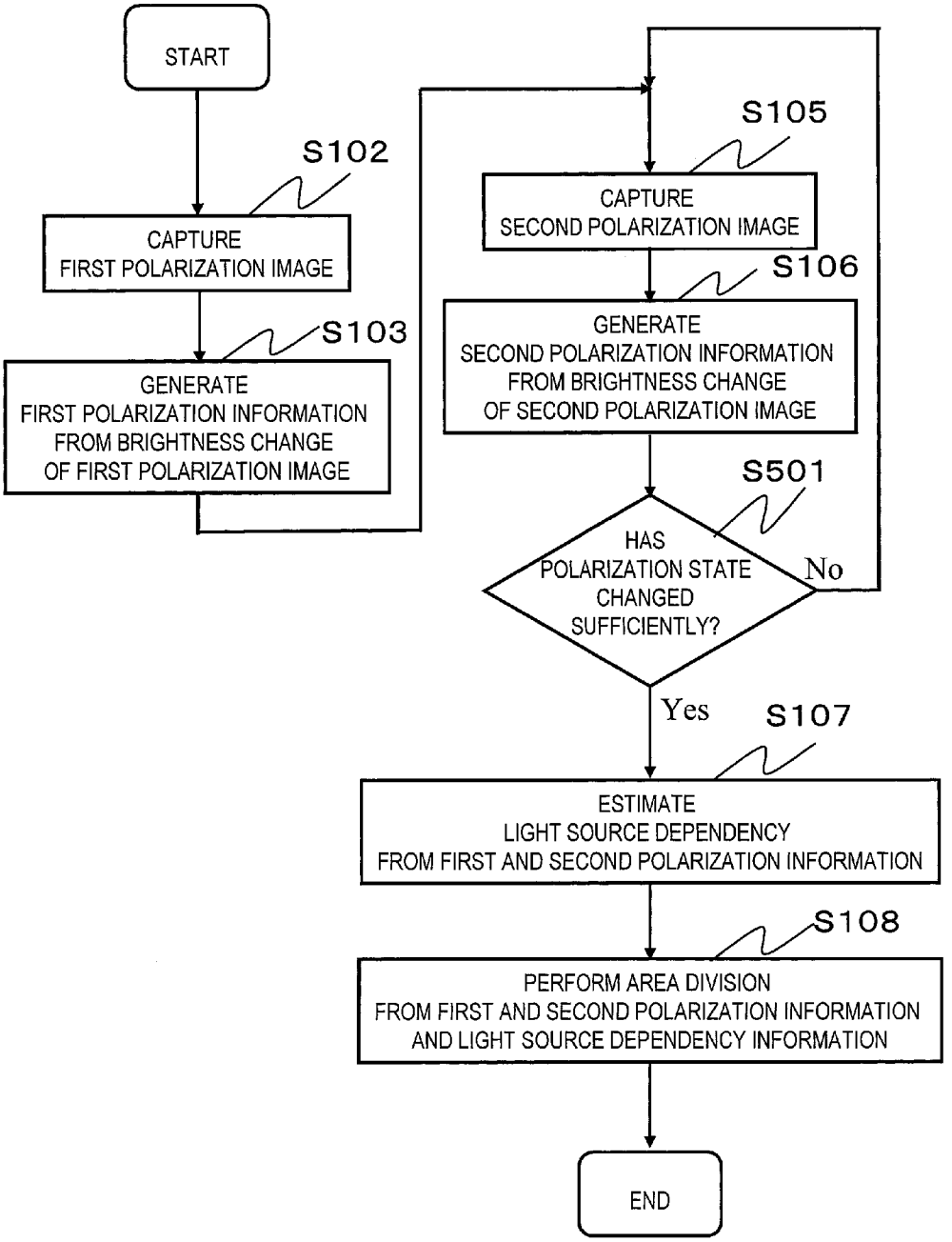

START
S102
CAPTURE FIRST POLARIZATION IMAGE
S103
GENERATE FIRST POLARIZATION INFORMATION FROM BRIGHTNESS CHANGE OF FIRST POLARIZATION IMAGE
S105
CAPTURE SECOND POLARIZATION IMAGE
S106
GENERATE SECOND POLARIZATION INFORMATION FROM BRIGHTNESS CHANGE OF SECOND POLARIZATION IMAGE
S501
HAS POLARIZATION STATE CHANGED SUFFICIENTLY?
No
Yes
S107
ESTIMATE LIGHT SOURCE DEPENDENCY FROM FIRST AND SECOND POLARIZATION INFORMATION
S108
PERFORM AREA DIVISION FROM FIRST AND SECOND POLARIZATION INFORMATION AND LIGHT SOURCE DEPENDENCY INFORMATION
END

FIG. 56

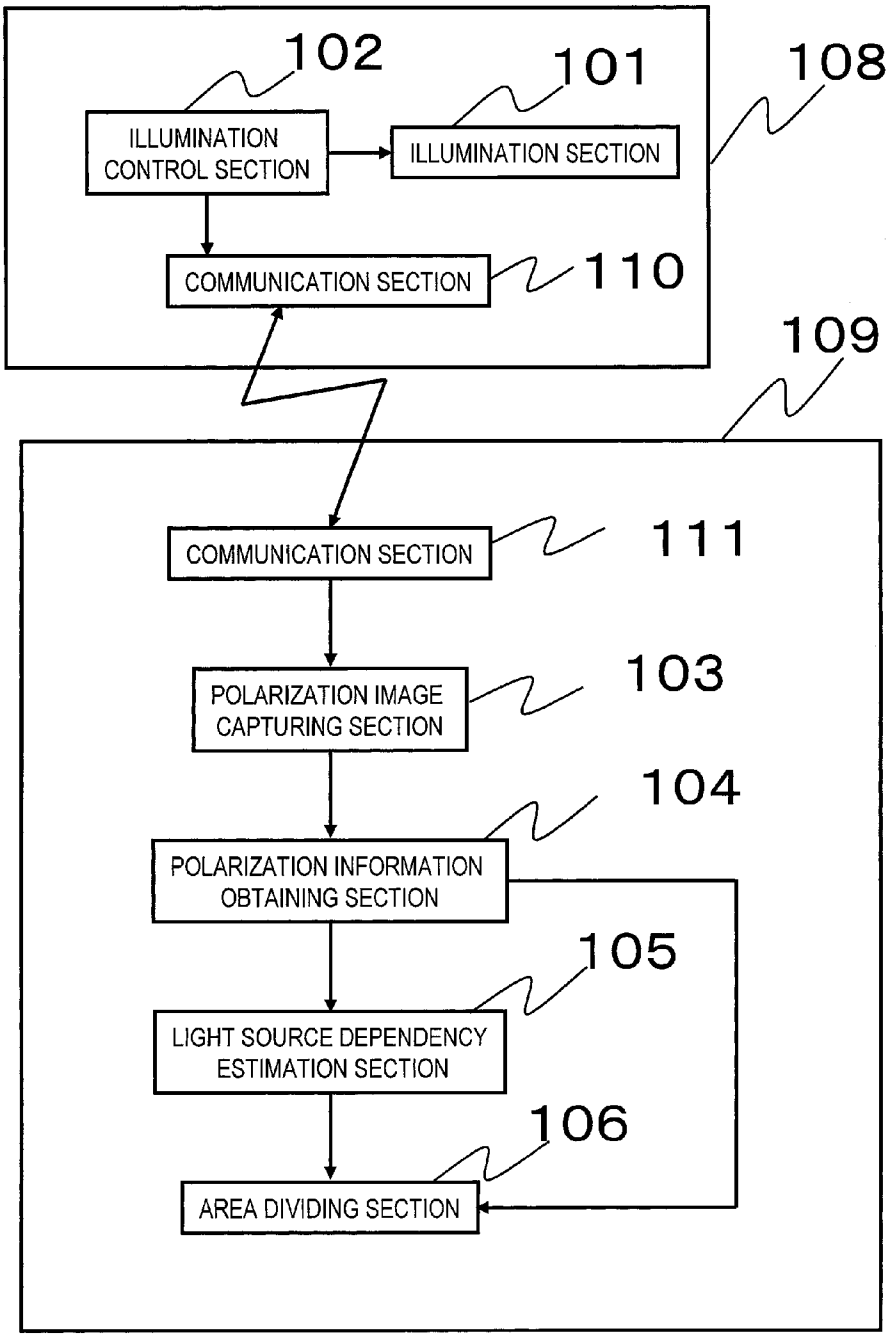

102
101
108
ILLUMINATION CONTROL SECTION
ILLUMINATION SECTION
COMMUNICATION SECTION
110
109
COMMUNICATION SECTION
111
POLARIZATION IMAGE CAPTURING SECTION
103
104
POLARIZATION INFORMATION OBTAINING SECTION
105
LIGHT SOURCE DEPENDENCY ESTIMATION SECTION
106
AREA DIVIDING SECTION

FIG. 57

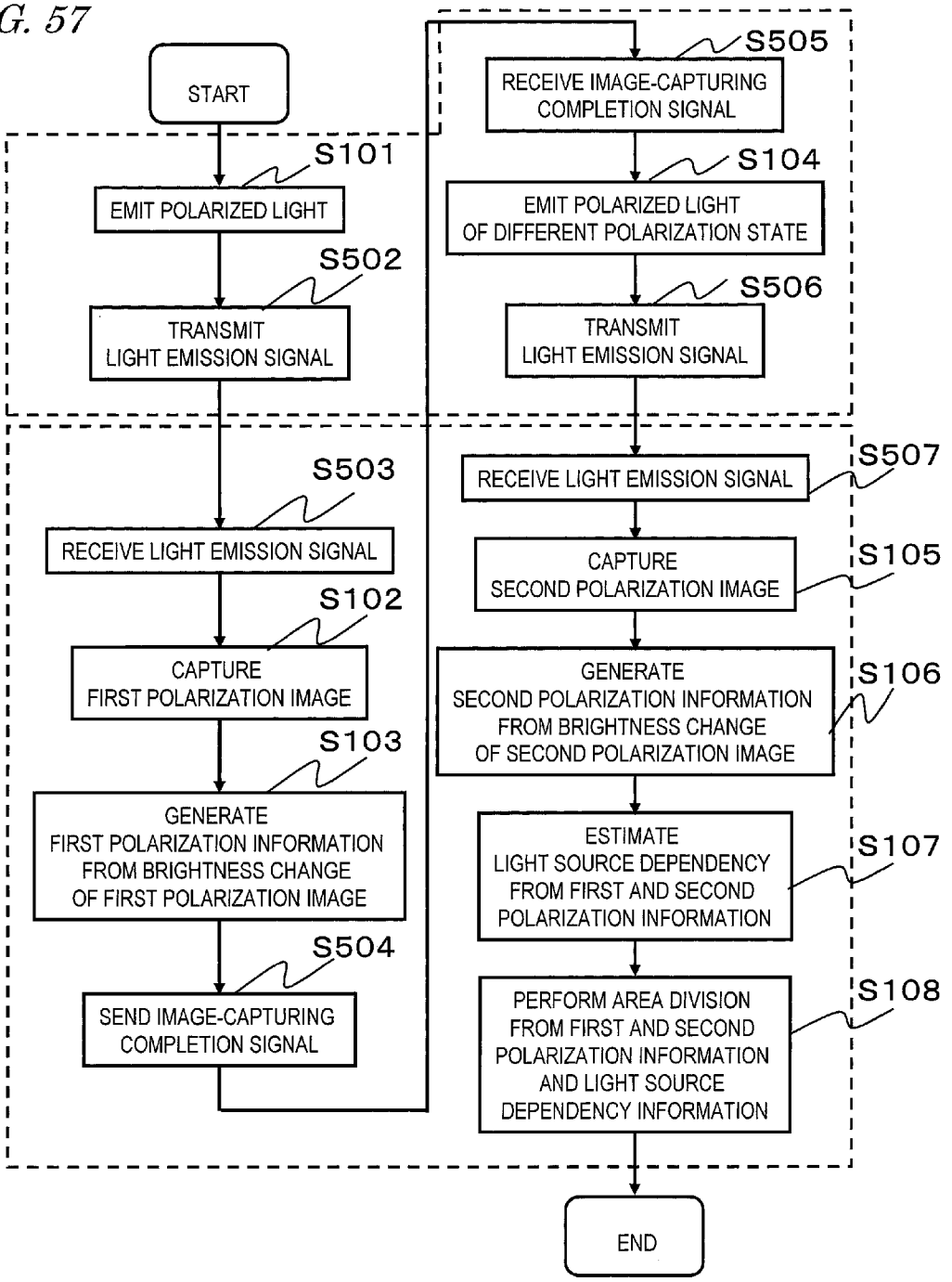

START
S101
EMIT POLARIZED LIGHT
S502
TRANSMIT LIGHT EMISSION SIGNAL
S503
RECEIVE LIGHT EMISSION SIGNAL
S102
CAPTURE FIRST POLARIZATION IMAGE
S103
GENERATE FIRST POLARIZATION INFORMATION FROM BRIGHTNESS CHANGE OF FIRST POLARIZATION IMAGE
S504
SEND IMAGE-CAPTURING COMPLETION SIGNAL
S505
RECEIVE IMAGE-CAPTURING COMPLETION SIGNAL
S104
EMIT POLARIZED LIGHT OF DIFFERENT POLARIZATION STATE
S506
TRANSMIT LIGHT EMISSION SIGNAL
S507
RECEIVE LIGHT EMISSION SIGNAL
S105
CAPTURE SECOND POLARIZATION IMAGE
S106
GENERATE SECOND POLARIZATION INFORMATION FROM BRIGHTNESS CHANGE OF SECOND POLARIZATION IMAGE
S107
ESTIMATE LIGHT SOURCE DEPENDENCY FROM FIRST AND SECOND POLARIZATION INFORMATION
S108
PERFORM AREA DIVISION FROM FIRST AND SECOND POLARIZATION INFORMATION AND LIGHT SOURCE DEPENDENCY INFORMATION
END

FIG. 58

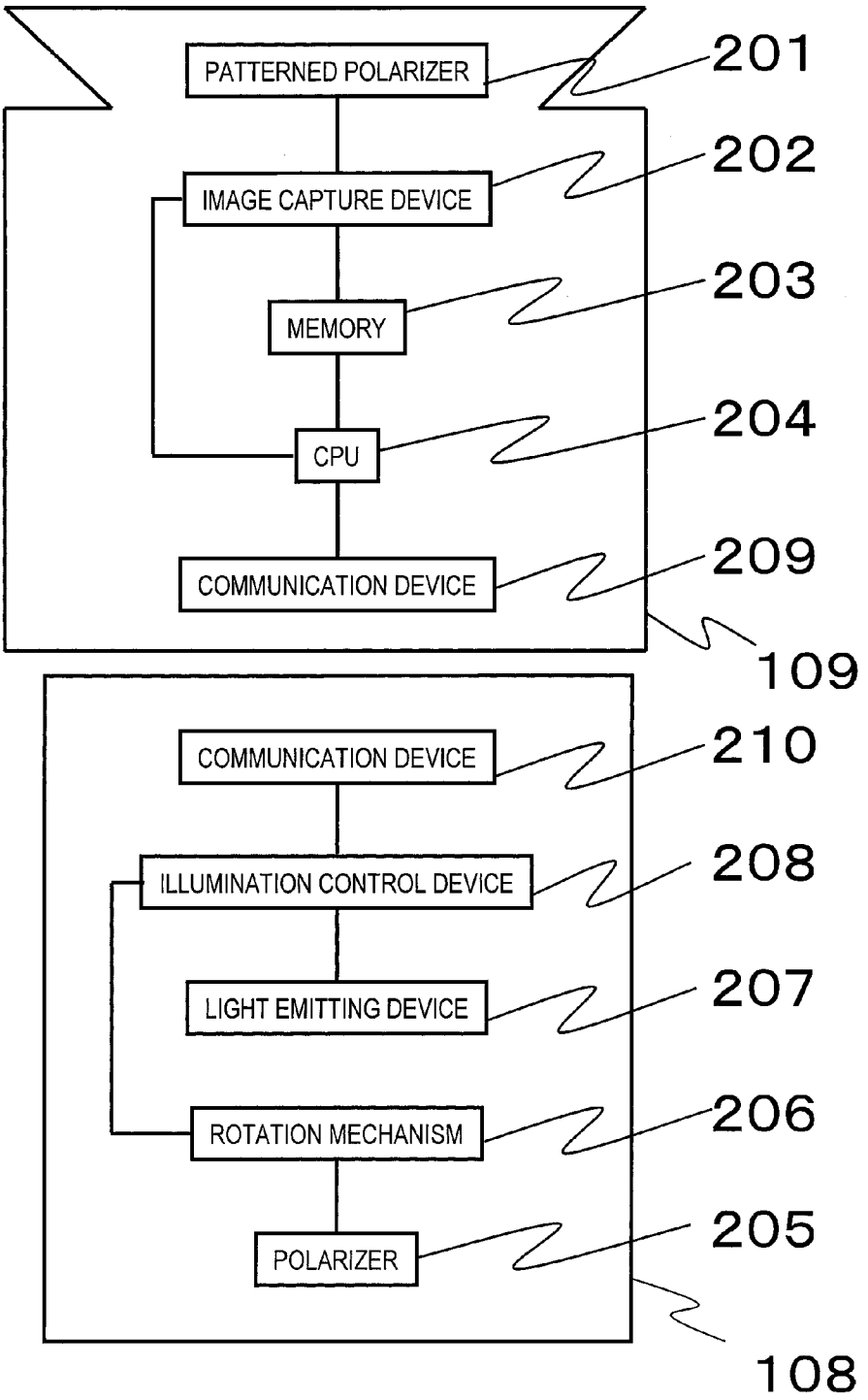

PATTERNED POLARIZER
201
IMAGE CAPTURE DEVICE
202
MEMORY
203
CPU
204
COMMUNICATION DEVICE
209
109
COMMUNICATION DEVICE
210
ILLUMINATION CONTROL DEVICE
208
LIGHT EMITTING DEVICE
207
ROTATION MECHANISM
206
POLARIZER
205
108

FIG. 59

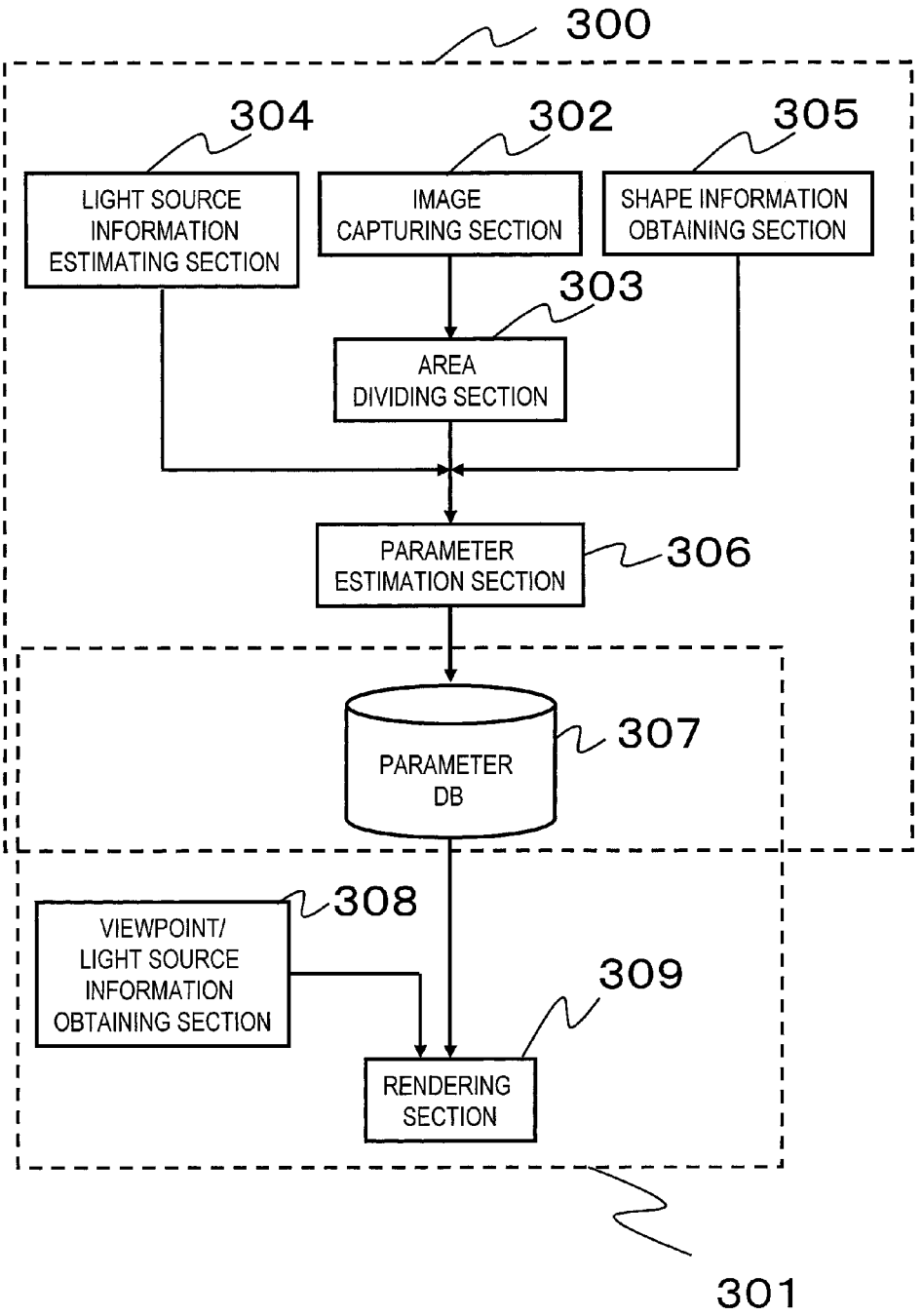

300
304
302
305
LIGHT SOURCE INFORMATION ESTIMATING SECTION
IMAGE CAPTURING SECTION
SHAPE INFORMATION OBTAINING SECTION
303
AREA DIVIDING SECTION
PARAMETER ESTIMATION SECTION
306
PARAMETER DB
307
308
VIEWPOINT/ LIGHT SOURCE INFORMATION OBTAINING SECTION
309
RENDERING SECTION
301

FIG. 60

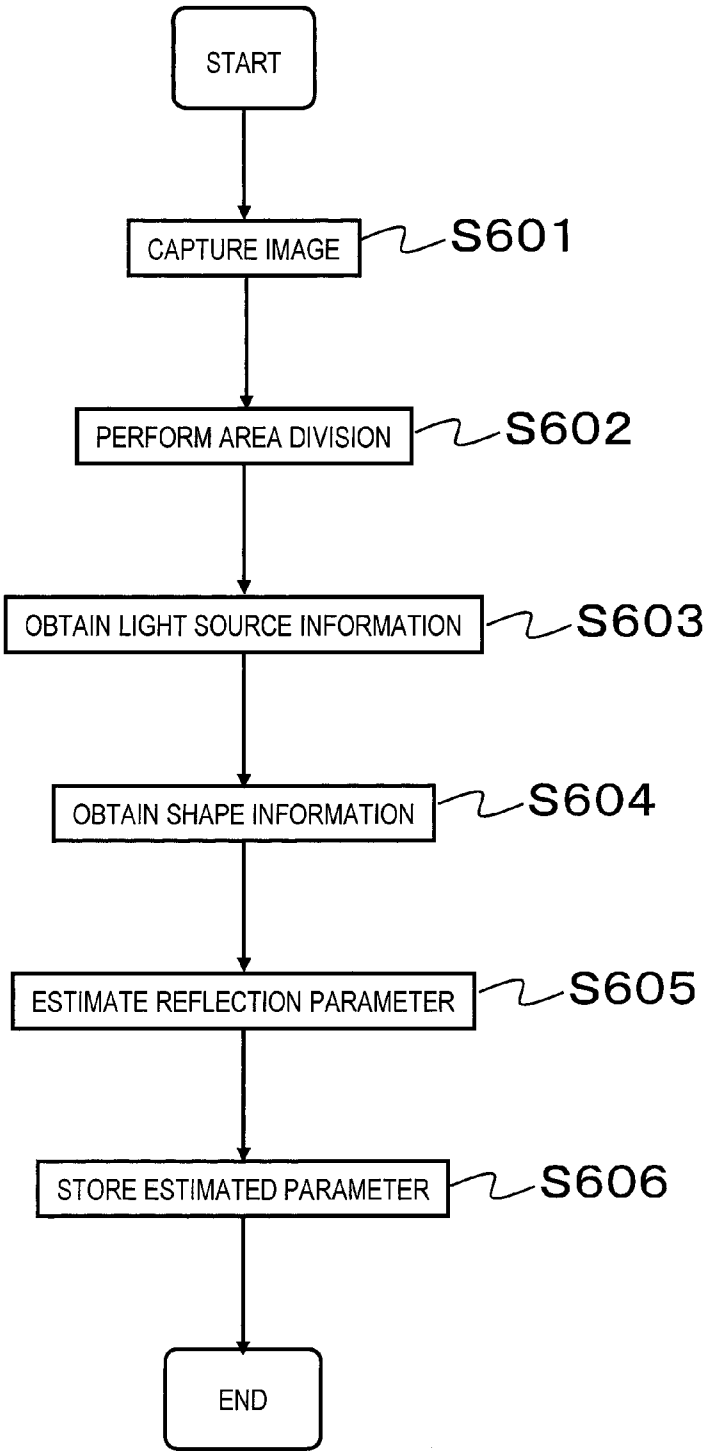

START
CAPTURE IMAGE
S601
PERFORM AREA DIVISION
S602
OBTAIN LIGHT SOURCE INFORMATION
S603
OBTAIN SHAPE INFORMATION
S604
ESTIMATE REFLECTION PARAMETER
S605
STORE ESTIMATED PARAMETER
S606
END

FIG. 61

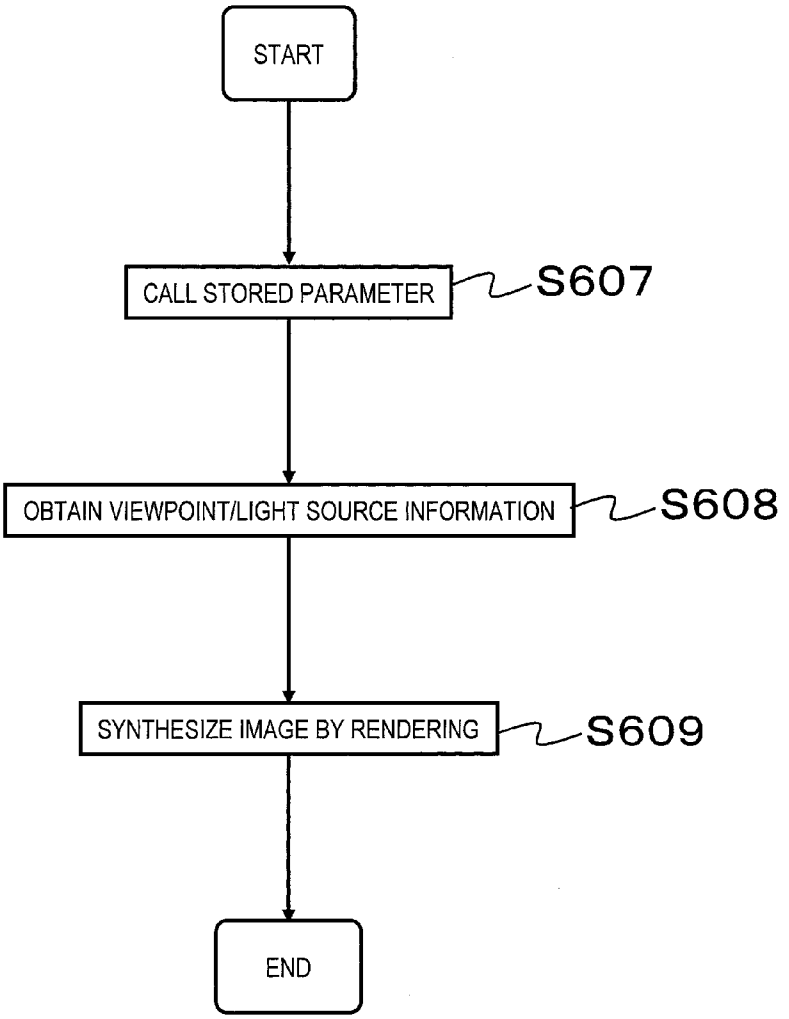

START
CALL STORED PARAMETER
S607
OBTAIN VIEWPOINT/LIGHT SOURCE INFORMATION
S608
SYNTHESIZE IMAGE BY RENDERING
S609
END

FIG. 62

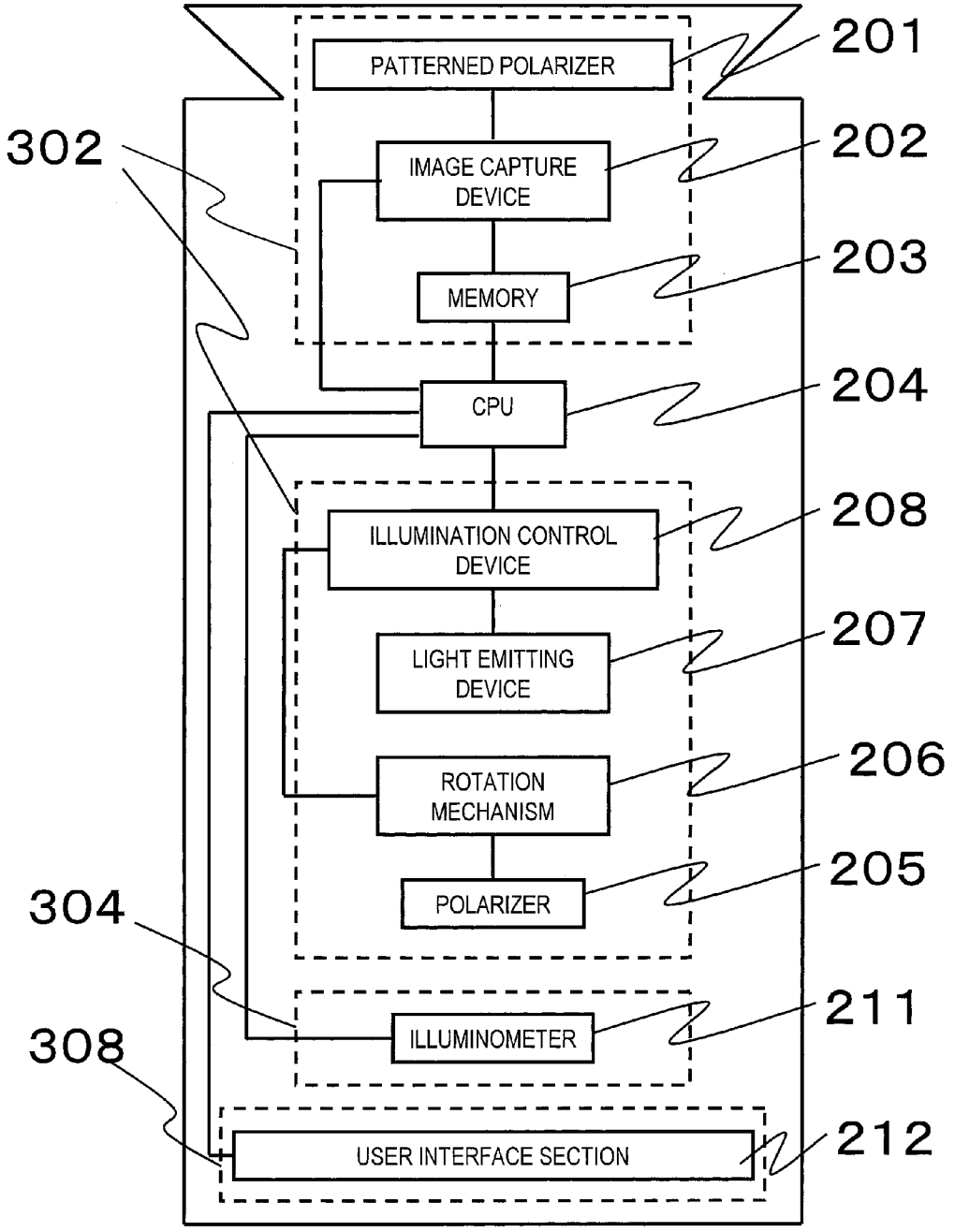

PATTERNED POLARIZER
201
302
IMAGE CAPTURE DEVICE
202
MEMORY
203
CPU
204
ILLUMINATION CONTROL DEVICE
208
LIGHT EMITTING DEVICE
207
ROTATION MECHANISM
206
POLARIZER
205
304
ILLUMINOMETER
211
308
USER INTERFACE SECTION
212

FIG. 63

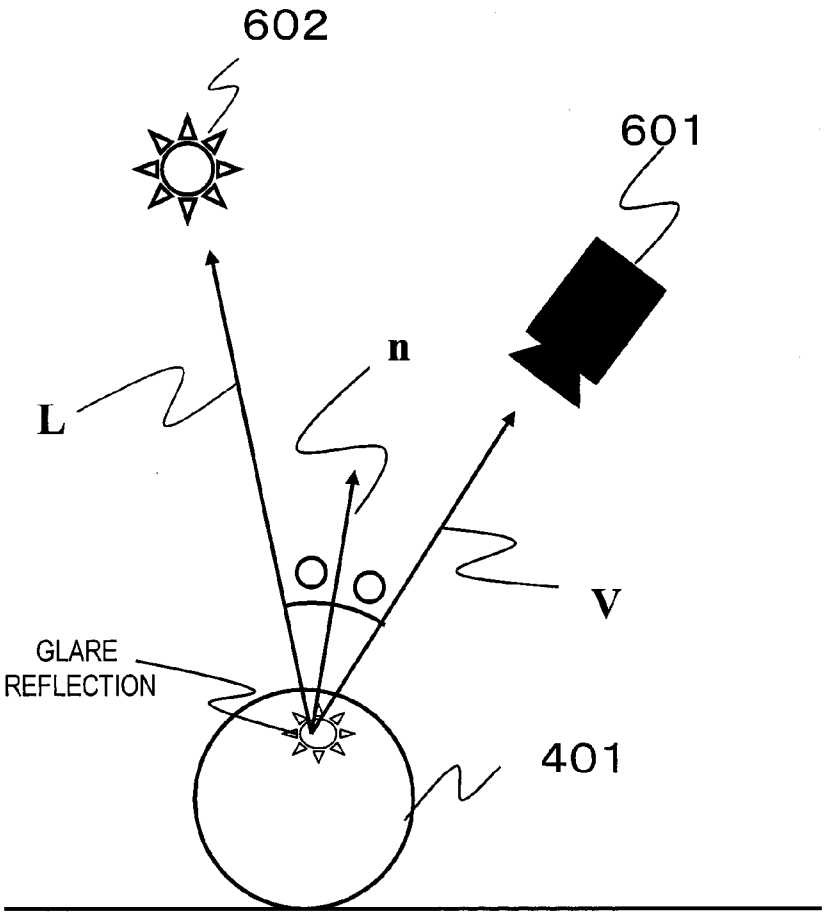


FIG. 64

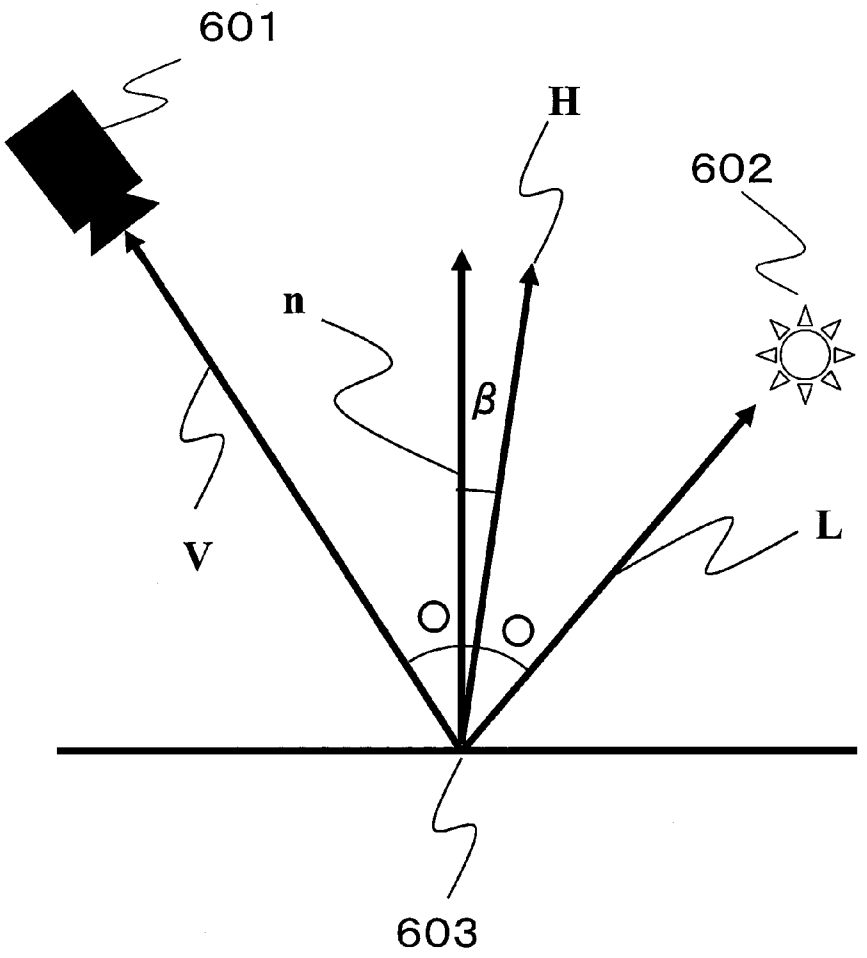


FIG. 65

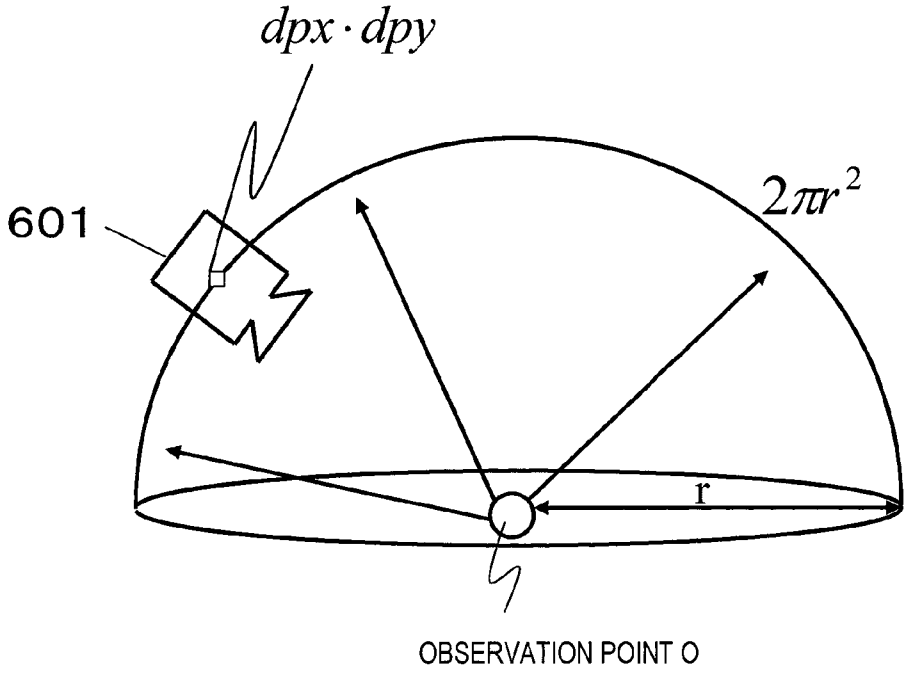


FIG. 66

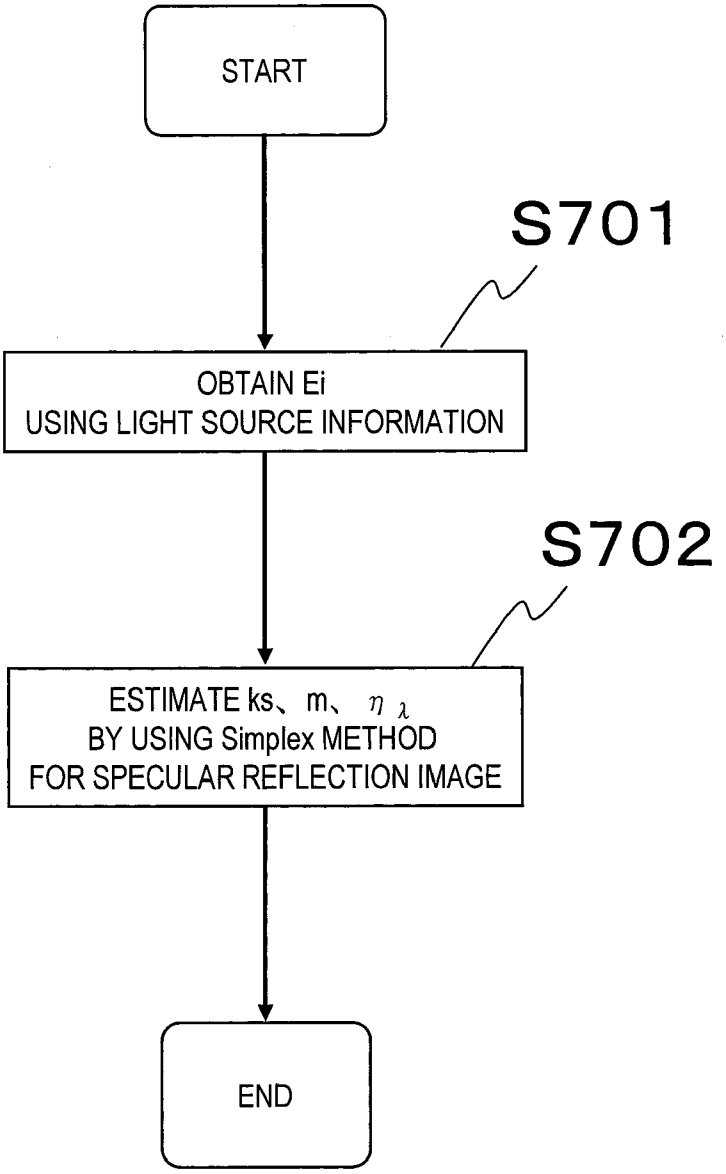

START
S701
OBTAIN Ei
USING LIGHT SOURCE INFORMATION
S702
ESTIMATE ks、 m、 η_λ
BY USING Simplex METHOD
FOR SPECULAR REFLECTION IMAGE
END

FIG. 67

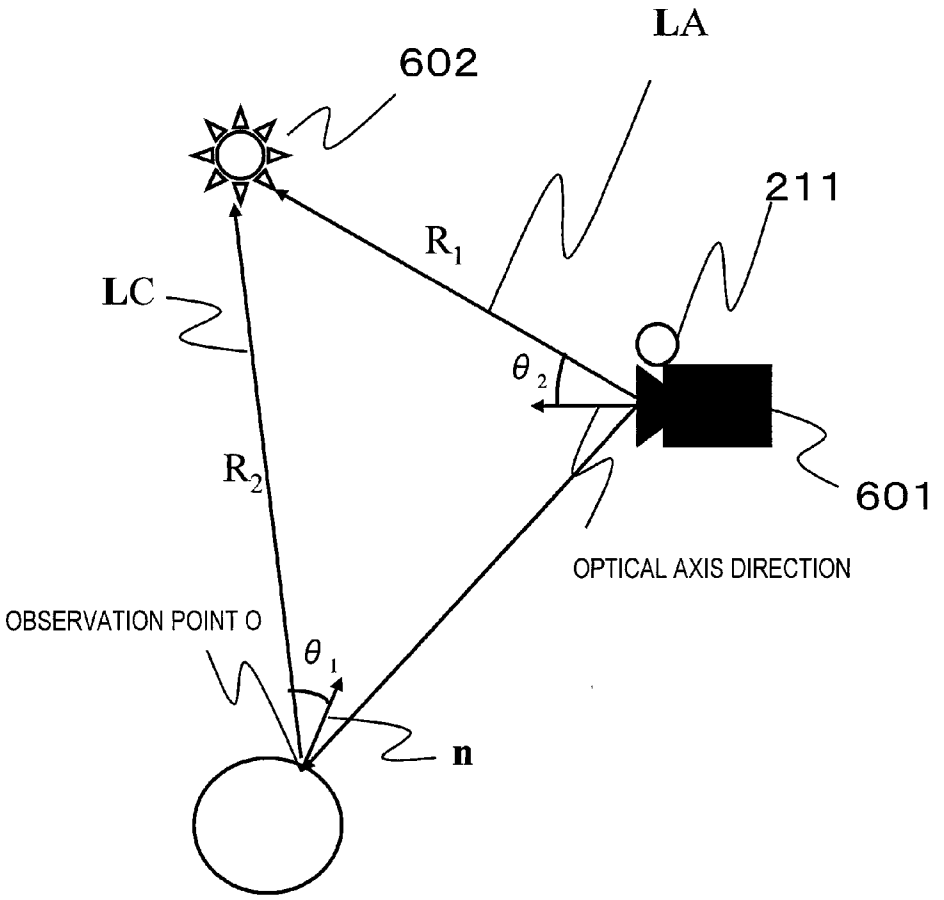

LA
602
211
R_1
LC
θ_2
R_2
601
OPTICAL AXIS DIRECTION
OBSERVATION POINT O
θ_1
n

FIG. 68

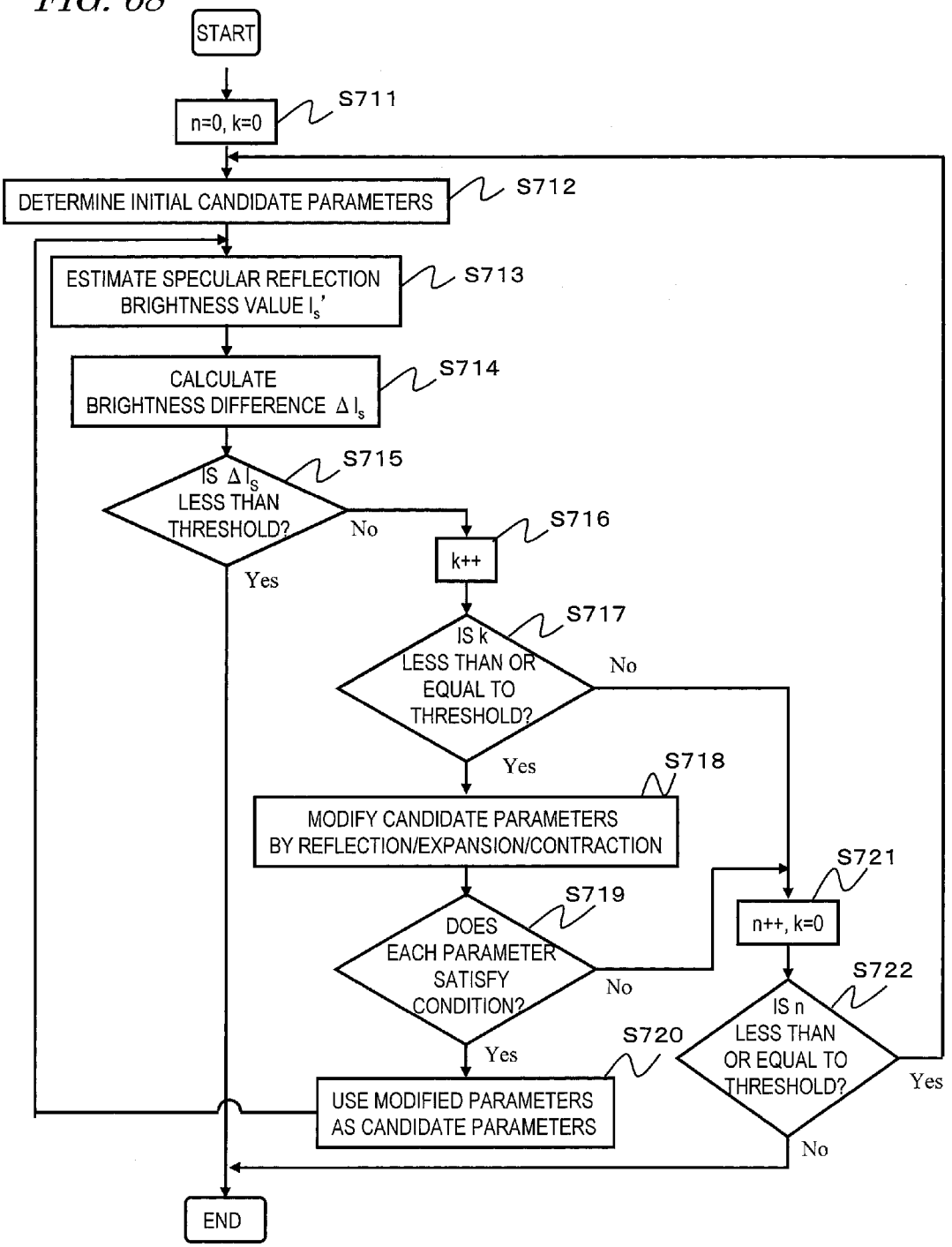

START
n=0, k=0
S711
DETERMINE INITIAL CANDIDATE PARAMETERS
S712
ESTIMATE SPECULAR REFLECTION BRIGHTNESS VALUE I_s'
S713
CALCULATE BRIGHTNESS DIFFERENCE ΔI_s
S714
IS ΔI_s LESS THAN THRESHOLD?
S715
No
Yes
k++
S716
IS k LESS THAN OR EQUAL TO THRESHOLD?
S717
No
Yes
MODIFY CANDIDATE PARAMETERS BY REFLECTION/EXPANSION/CONTRACTION
S718
DOES EACH PARAMETER SATISFY CONDITION?
S719
No
Yes
USE MODIFIED PARAMETERS AS CANDIDATE PARAMETERS
S720
n++, k=0
S721
IS n LESS THAN OR EQUAL TO THRESHOLD?
S722
Yes
No
END

FIG. 69

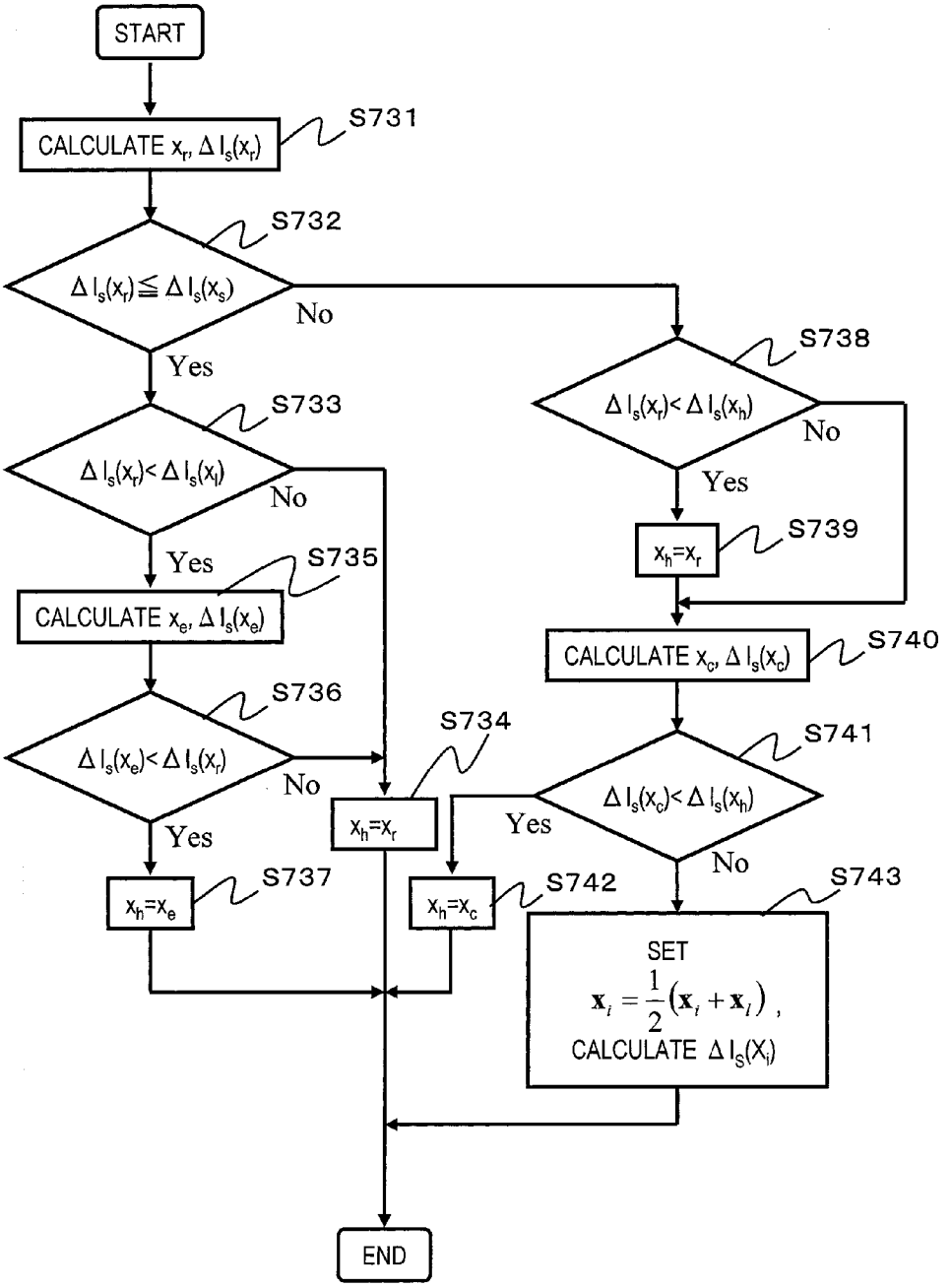

START
CALCULATE x_r, $\Delta I_s(x_r)$
S731
S732
$\Delta I_s(x_r) \leqq \Delta I_s(x_s)$
No
Yes
S733
$\Delta I_s(x_r) < \Delta I_s(x_l)$
No
Yes
S735
CALCULATE x_e, $\Delta I_s(x_e)$
S736
$\Delta I_s(x_e) < \Delta I_s(x_r)$
No
Yes
S734
$x_h = x_r$
S737
$x_h = x_e$
S738
$\Delta I_s(x_r) < \Delta I_s(x_h)$
No
Yes
S739
$x_h = x_r$
S740
CALCULATE x_c, $\Delta I_s(x_c)$
S741
$\Delta I_s(x_c) < \Delta I_s(x_h)$
Yes
No
S742
$x_h = x_c$
S743
SET
$\mathbf{x}_i = \frac{1}{2}(\mathbf{x}_i + \mathbf{x}_l)$,
CALCULATE $\Delta I_S(X_i)$
END

FIG. 70

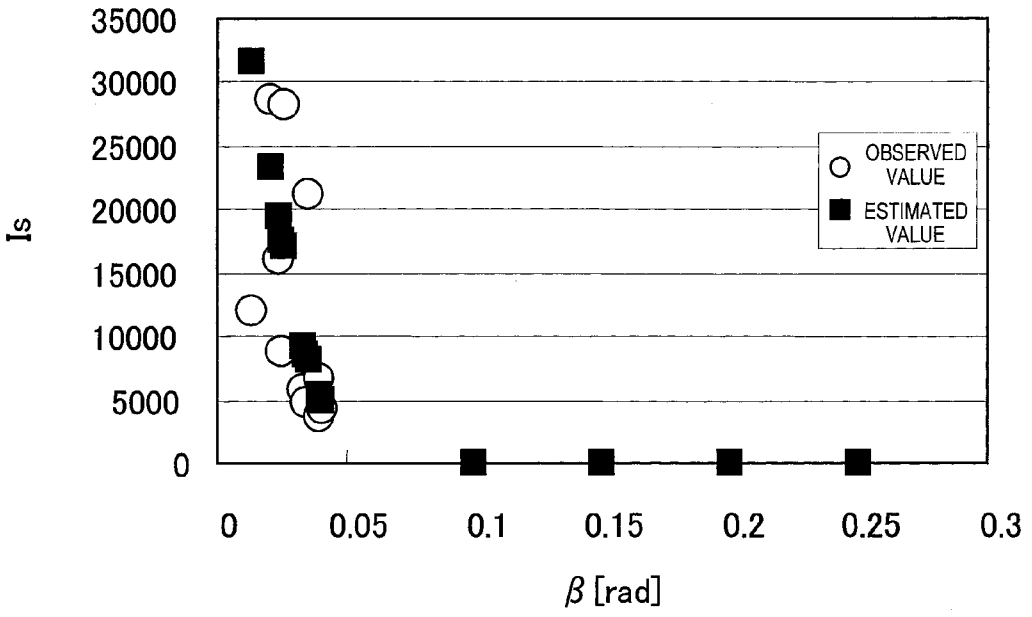

35000
30000
25000
20000
15000
10000
5000
0
Is
0
0.05
0.1
0.15
0.2
0.25
0.3
β [rad]
OBSERVED VALUE
ESTIMATED VALUE

FIG. 71

PIXEL POSITION (x,y)	...	(100,200)	...
ALBEDO ρ d (PSEUDO-ALBEDO tf ρ dp)	...	(200,200,100)	...
SPECULAR REFLECTION COMPONENT COEFFICIENT ks	...	0.8	...
REFRACTIVE INDEX η	...	1.4	...
ROUGHNESS m	...	0.3	...
NORMAL x DIRECTION nx	...	0.43	...
NORMAL y DIRECTION ny	...	0.31	...
NORMAL z DIRECTION nz	...	-0.85	...

FIG. 72

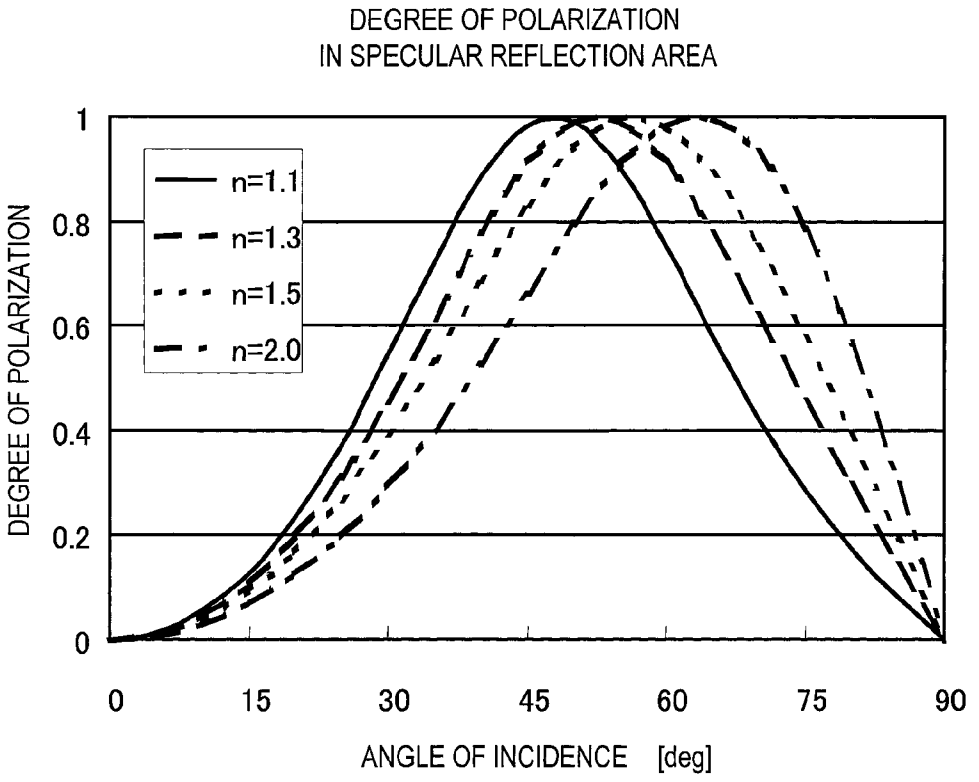

DEGREE OF POLARIZATION
IN SPECULAR REFLECTION AREA
DEGREE OF POLARIZATION
1
0.8
0.6
0.4
0.2
0
n=1.1
n=1.3
n=1.5
n=2.0
0
15
30
45
60
75
90
ANGLE OF INCIDENCE [deg]

FIG. 73

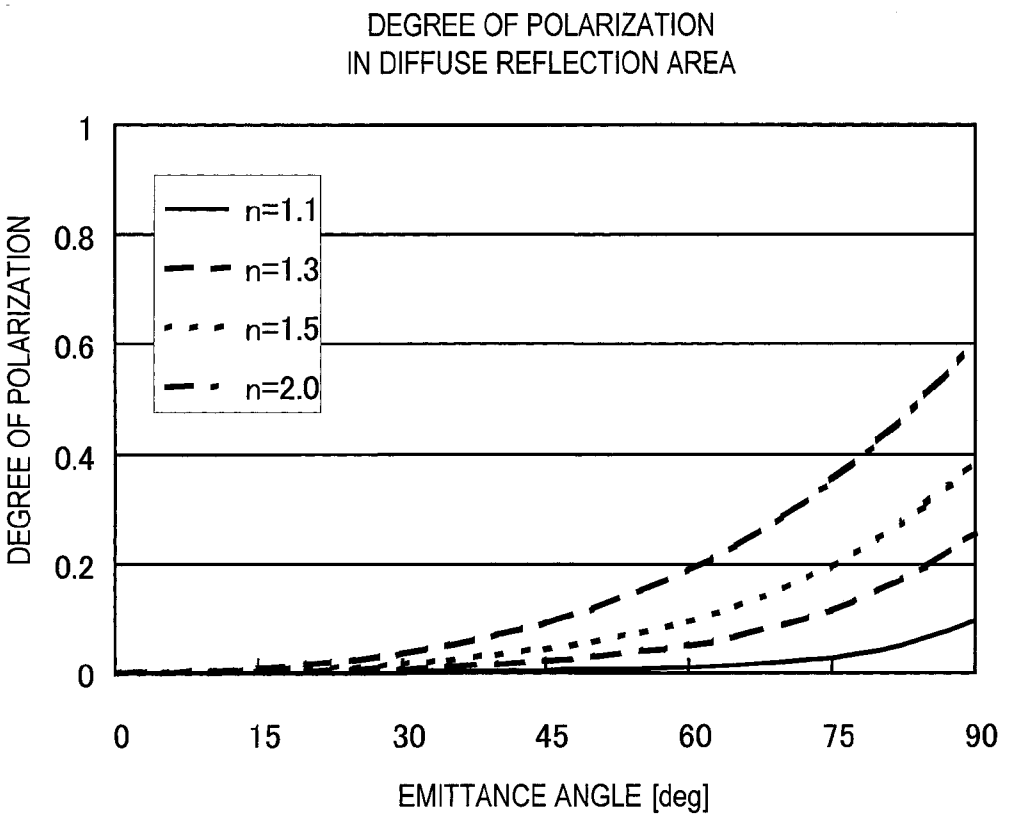

DEGREE OF POLARIZATION
IN DIFFUSE REFLECTION AREA
DEGREE OF POLARIZATION
1
0.8
0.6
0.4
0.2
0
n=1.1
n=1.3
n=1.5
n=2.0
0
15
30
45
60
75
90
EMITTANCE ANGLE [deg]

FIG. 74

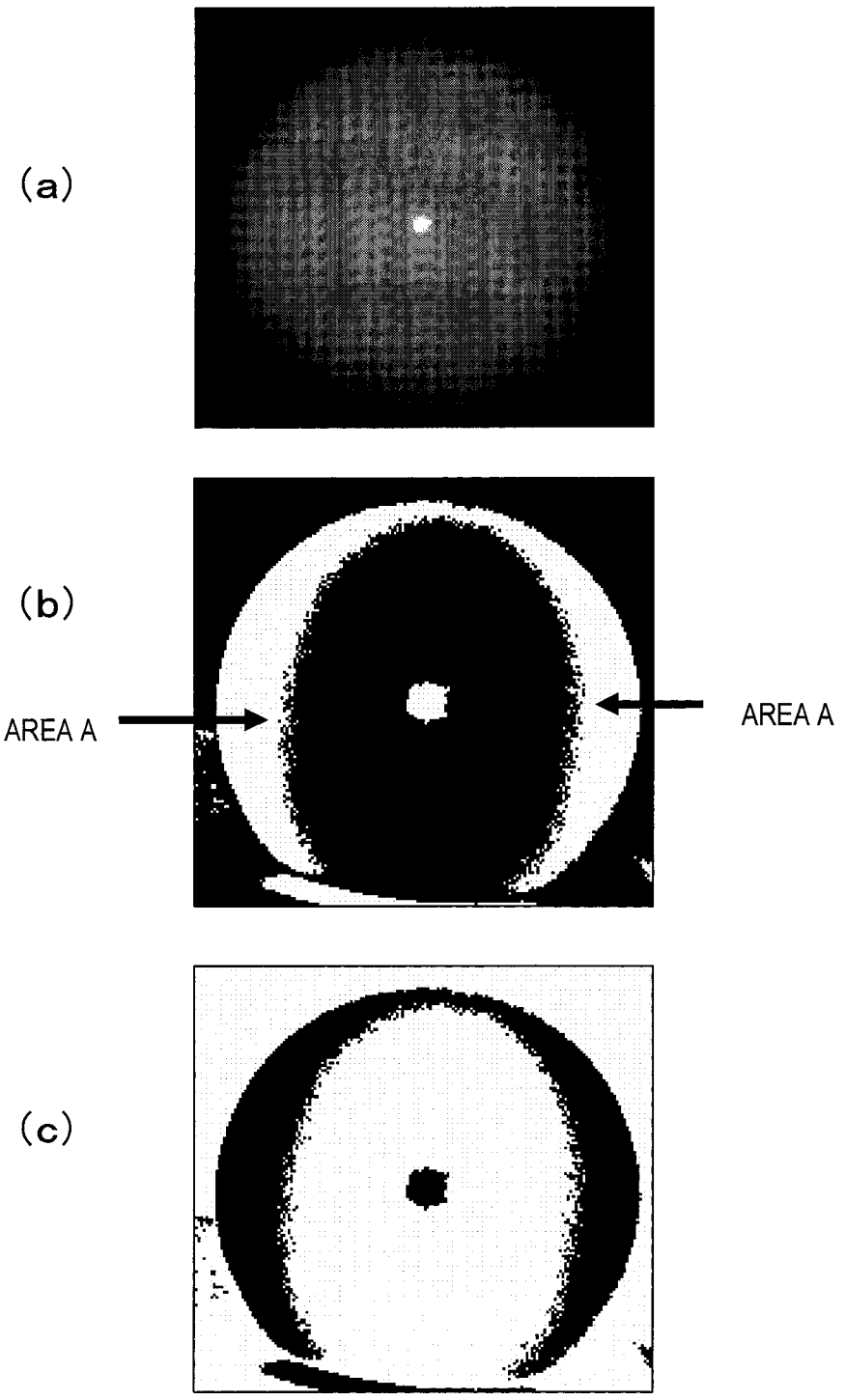
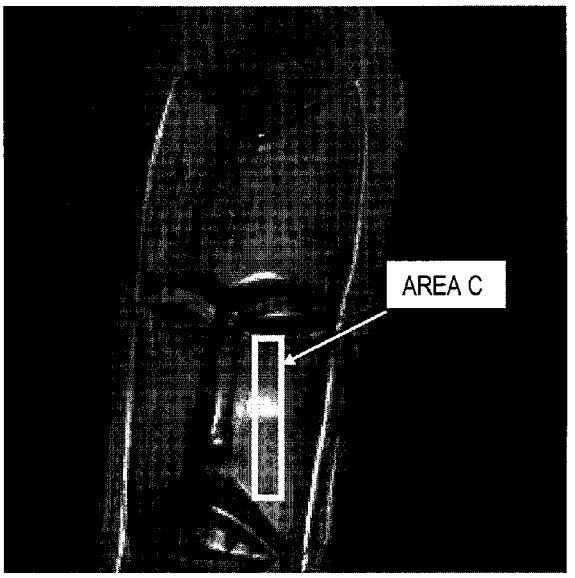
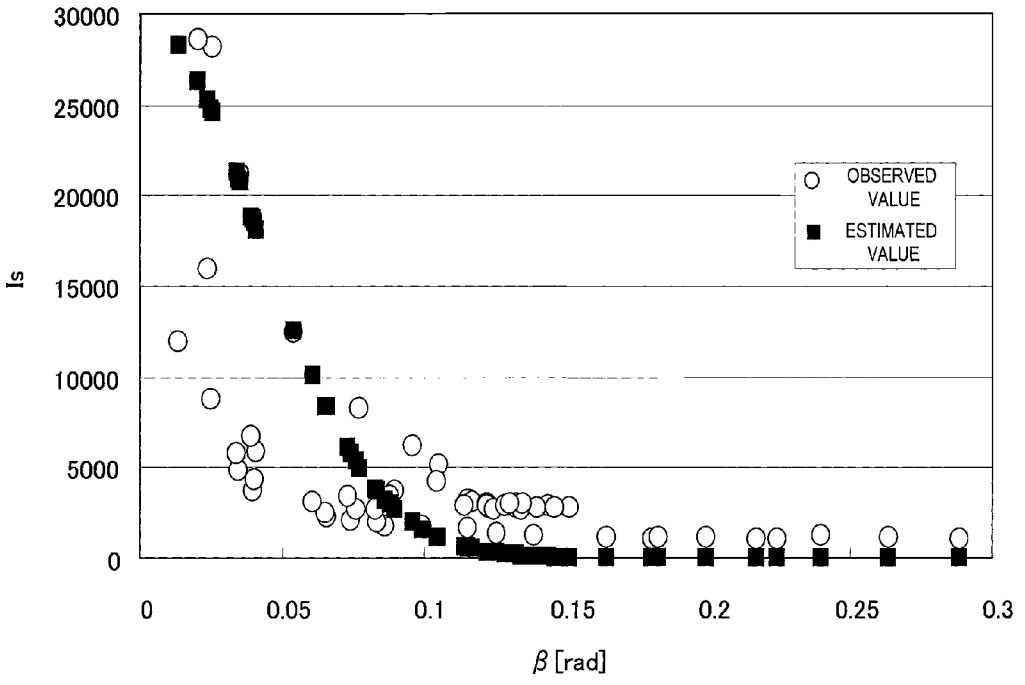


FIG. 75


AREA C

(a)


30000
25000
20000
15000
10000
5000
0
Is
0
0.05
0.1
0.15
0.2
0.25
0.3
β [rad]
OBSERVED VALUE
ESTIMATED VALUE

(b)

FIG. 76

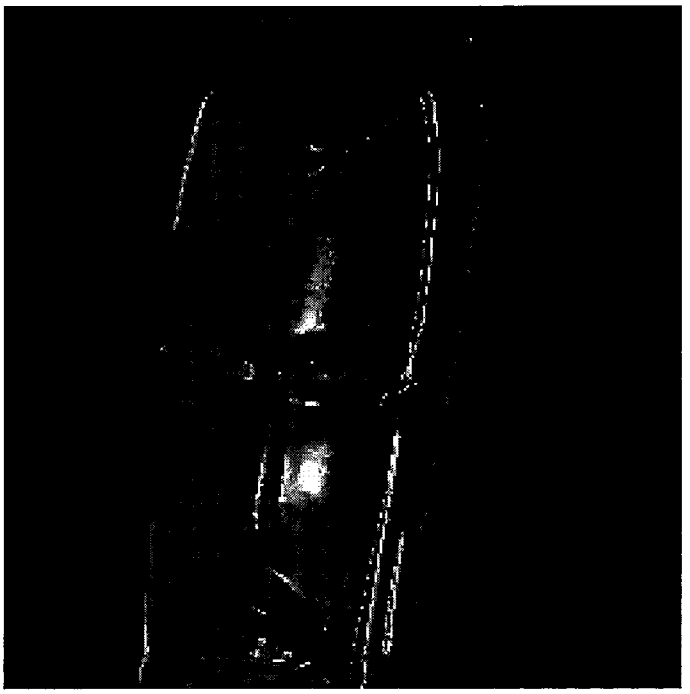


IMAGE PROCESSING APPARATUS, IMAGE DIVISION PROGRAM AND IMAGE SYNTHESISING METHOD

TECHNICAL FIELD

[0001] The present invention relates to an image processing technique, and more particularly to a technique for improving the precision of image division, which has been an issue when obtaining shape information of an object and when synthesizing an image.

BACKGROUND ART

[0002] It is known that the appearance of an object is composed of a plurality of components such as a specular reflection component, which is the incident light reflected by the surface of the object being observed as a "gloss", and a diffuse reflection component observed as light repeatedly scattered inside the object.

[0003] In recent years, methods have been widely employed in which an image is separated into such components for compressing the information for digital archives or for obtaining the shape/surface material of the object (e.g., Non-Patent Document 1, Non-Patent Document 2 and Non-Patent Document 3). This is because a process with a higher precision can be achieved by performing a process for each of the separated components.

[0004] As the method for separating an image into different components as described above, a method for separating it into a specular reflection component and a diffuse reflection component has been widely used. Particularly, a method utilizing polarization information has been widely researched because specular reflection and diffuse reflection can be separated with a simple device. In this method, a linearly-polarized light source is emitted onto the object, and the specular reflection component and the diffuse reflection component are separated from each other by rotating a linear polarization filter provided between the camera and the object about the optical axis.

[0005] It is known that where Φ is the rotation angle (polarization main axis angle) of the linear polarization filter, the luminance value observed in each pixel changes along a sinusoidal function with respect to the rotation angle Φ. The image separation can be done by determining the amplitude component of the sinusoidal function as the "specular reflection component" and the bias component as the "diffuse reflection component". That is, for each of a plurality of pixels of an image, the pixel can be assigned as a "specular reflection area" or a "diffuse reflection area" depending on whether the specular reflection component or the diffuse reflection component is dominant. In other words, pixels where the specular reflection component is dominant form a "specular reflection area", and pixels where the diffuse reflection component is dominant form a "specular reflection area".

[0006] A method for performing an area division for the surface of an object as described above can be realized based on the difference in polarization characteristics between specular reflection and diffuse reflection.

[0007] Since the specular reflection component occurs from surface reflection, the polarization characteristics of the incident light are maintained. Therefore, it is observed as the polarized component of the brightness observed by the camera.

[0008] Since the diffuse reflection occurs through repeated scattering, the polarization characteristics of the incident light have been lost. Therefore, it is observed as the non-polarized component of the brightness observed by the camera.

[0009] These polarization characteristics are based on the following two conditions.

(Condition 1) Where linearly-polarized light is emitted, a specular reflection component is observed as a polarized component.

(Condition 2) Where linearly-polarized light is emitted, a diffuse reflection component is observed as a non-polarized component.

[0010] Referring to FIGS. **74**(*a*)-(c), a conventional area division will be described.

[0011] FIGS. **74**(*b*) and (*c*) show the specular reflection area and the diffuse reflection area, respectively, obtained by dividing the image of FIG. **74**(*a*) by a conventional area division. That is, areas denoted by white pixels in FIG. **74**(*b*) are those divided as "specular reflection areas", whereas areas denoted by white pixels in FIG. **74**(*c*) are those divided as "diffuse reflection areas".

[0012] As seen from these images, the peripheral portion of the sphere near the occluding edge (the area A in FIG. **74**(*b*)) is divided as a "specular reflection area". However, specular reflection occurs in or near a regular reflection area. A specular reflection component being estimated in such an occluding edge area indicates that the separation precision is not sufficient.

[0013] Such a problem occurs as (Condition 2) is not satisfied because a portion of the diffuse reflection component is polarized. The cause of such a problem will be discussed below with reference to FIGS. **72** and **73**.

[0014] FIGS. **72** and **73** are graphs showing the degree of polarization of the specular reflection component and the degree of polarization of the diffuse reflection component, respectively, for objects whose refractive indices are n=1.1, 1.3, 1.5 and 2.0 (see, for example, L. B. Wolff and T. E. Boult, "Constraining object features using a polarization reflectance model", IEEE Transactions on Pattern Analysis and Machine Intelligence, Vol. 13, No. 7, pp. 635-657, 1991). The horizontal axis of the graph of FIG. **72** represents the angle of incidence, and the vertical axis represents the degree of polarization, whereas the horizontal axis of the graph of FIG. **73** represents the emittance angle, and the vertical axis represents the degree of polarization. The following can be known from the figures.

[0015] The degree of polarization of the diffuse reflection component is sufficiently small except for areas where the emittance angle is sufficiently large.

[0016] The degree of polarization of the diffuse reflection component is sufficiently larger than the degree of polarization of the specular reflection component in areas where the emittance angle is sufficiently large.

[0017] That is, the following can be known.

[0018] (Condition 2) holds except for areas where the emittance angle is sufficiently large.

[0019] (Condition 2) does not hold in areas where the emittance angle is sufficiently large.

[0020] This is a major reason why the conventional area division shown in FIG. **74** failed to accurately separate the specular reflection component and the diffuse reflection component from each other.

CITATION LIST

Patent Literature

[0021] [Non-Patent Document 1] Y. Sato, M. D. Wheeler, and K. Ikeuchi, "Object shape and reflectance modeling from observation", SIGGRAPH 97, pp. 379-387, 1997

[0022] [Non-Patent Document 2] Daisuke Miyazaki, Takushi Shibata, Katsushi Ikeuchi, "Wavelet-Texture Method: BTF Compression by Using Daubechies Wavelet, Parametric Reflection Model, and Circular Polarizer", Trans. of IEICE, Vol. J90-D No. 8, pp. 2081-2093, 2007

[0023] [Non-Patent Document 3] T. Shibata, T. Takahashi, D. Miyazaki, Y. Sato, K. Ikeuchi, "Creating Photorealistic Virtual Model with Polarization Based Vision System", in Proceedings of SPIE (Polarization Science and Remote Sensing II, Part of SPIE's International Symposium on Optics and Photonics 2005), Vol. 5888, pp. 25-35, 2005

SUMMARY OF INVENTION

Technical Problem

[0024] The importance of such a problem will be even greater in the future as the dynamic range of recent cameras has been increased. With conventional cameras, the brightness dynamic range is not sufficiently large, and the degree of polarization of diffuse reflection is unlikely to be observed. However, with the increased dynamic range of cameras in recent years, the deterioration in the separation precision described above will be a significant problem.

[0025] The deterioration in the separation precision between the specular reflection component and the diffuse reflection component will be a significant problem of synthesizing together images of substantially different textures when performing a model-based image synthesis, which has been used in the fields of digital archives and augmented reality. The model-based image synthesis is a technique widely used in the CG (Computer Graphics) field. Since various image processes such as a viewpoint changing process and a light source environment changing process can be done, it is very effective for digital archives and as a method of interactive image presentation. It also enables an efficient data compression. As an example, a method is known in the art where an image is separated into the specular reflection component and the diffuse reflection component, and the image is modeled by using the Cook-Torrance model for the specular reflection component and the Lambertian model for the diffuse reflection component.

[0026] For the image shown in FIG. **75**(*a*), data shown in the graph of FIG. **75**(*b*) was obtained for the area C of the object. FIG. **75**(*b*) is a graph representing the half-way vector β between the viewing vector and the illumination direction vector along the horizontal axis, and the luminance value Is of the specular reflection component along the vertical axis, for the area C of FIG. **75**(*a*). In the graph of FIG. **75**(*b*), the open circular dots are obtained by plotting the luminance value Is observed for the area C. The solid squares are obtained by plotting the estimation of the reflection parameters of the Cook-Torrance model. From this figure, it can be seen that the model fitting is not working well.

[0027] FIG. **76** shows a synthesized image produced by using a conventional area dividing approach. Thus, when an image is synthesized by using mis-estimated parameters, the texture of the synthesized image will be substantially different from the actual texture. A reason for such an estimation failure is that the luminance value Is is estimated to be larger than the actual value particularly in areas where the half-way vector p is large due to the deterioration in the separation precision between the specular reflection component and the diffuse reflection component described above. The insufficient separation precision between the specular reflection component and the diffuse reflection component results in using the specular reflection component and the diffuse reflection component, which are different from the actual components, when estimating parameters in each model. Therefore, the process estimates model parameters that are different from the actual model parameters. As described above, an accurate area division of an image is very important in model-based image synthesis.

Solution to Problem

[0028] An image processing apparatus of the present invention is an image processing apparatus for capturing an image of an object and thereby performing an optical area division of a surface of the object, comprising: a polarization image capturing section for obtaining a polarization image of the object by receiving light having passed through a three-way or more polarizer having different polarization main axis angles, wherein the area division is performed based on a polarization state on the surface of the object and a light source dependency, which represents a degree of change in the polarization state on the surface of the object occurring when changing at least one of a polarization state of light emitted from a light source and a light source position.

[0029] In a preferred embodiment, it comprises an illumination unit including the light source and being capable of changing at least one of the polarization state of light emitted from the light source and the light source position; and a control section for synchronizing the changing by the illumination unit of at least one of the polarization state of light emitted from the light source and the light source position with the image-capturing by the polarization image capturing section.

[0030] In a preferred embodiment, it comprises: an illumination control section for changing the polarization state of the linearly-polarized light emitted from the light source; a polarization information obtaining section for generating, from the obtained polarization image, polarization information for received polarized light by using a correspondence with a brightness of the light having passed through the three-way or more polarizer, for each of unit pixels of the polarization image; a light source dependency estimation section for estimating light source dependency information by making a comparison between the polarization information generated by the polarization information obtaining section when the polarization state of light emitted from the light source is changed by the illumination control section; and an area dividing section for performing the area division based on the polarization information generated by the polarization information obtaining section and light source variation information estimated by the light source dependency estimation section.

[0031] In a preferred embodiment, the polarization information obtaining section generates, as the polarization information, at least one of a degree of polarization, a polarization phase, a polarization estimation error, a polarization maximum luminance value, and a polarization minimum luminance value.

[0032] In a preferred embodiment, the area dividing section performs the area division so that the surface of the object is divided into areas each being a diffuse reflection area or a specular reflection area.

[0033] In a preferred embodiment, the area dividing section performs the area division so that the surface of the object is divided into areas each being a diffuse reflection non-polarized area, a diffuse reflection polarized area, or a specular reflection polarized area.

[0034] In a preferred embodiment, the area dividing section performs the area division so that the surface of the object is divided into areas each being a light source-dependent polarized area, a light source-dependent non-polarized area, a light source-independent polarized area, or a light source-independent non-polarized area.

[0035] In a preferred embodiment, the area dividing section performs the area division so that the surface of the object is further divided into areas including a shaded area.

[0036] In a preferred embodiment, the illumination control section changes a main axis direction of the linearly-polarized light.

[0037] In a preferred embodiment, the illumination control section changes a main axis direction of the linearly-polarized light by 90 degrees.

[0038] In a preferred embodiment, it comprises a plurality of illumination sections of different polarization states, wherein the illumination control section changes the polarization state by switching between the plurality of illumination sections.

[0039] In a preferred embodiment, an illumination section is present near the polarization image capturing section.

[0040] In a preferred embodiment, the light source dependency estimation section estimates, as the polarization dependency, the value of change of at least one of the polarization phase and the degree of polarization.

[0041] In a preferred embodiment, it comprises: an illumination position changing section for changing the position of the light source; a polarization information obtaining section for generating, from the obtained polarization image, polarization information for received polarized light by using a correspondence with a brightness of the light having passed through the three-way or more polarizer, for each of unit pixels of the polarization image; a light source dependency estimation section for estimating light source dependency information by making a comparison between the polarization information generated by the polarization information obtaining section when the position of the light source is changed by the illumination control section; and an area dividing section for performing the area division based on the polarization information generated by the polarization information obtaining section and light source variation information estimated by the light source dependency estimation section.

[0042] In a preferred embodiment, it comprises a plurality of illumination sections of different light source positions, wherein the illumination position changing section changes a position of illumination section by switching between the plurality of illumination sections.

[0043] In a preferred embodiment, the illumination position changing section changes the light source position by moving an illumination section.

[0044] In a preferred embodiment, the area dividing section performs the area division so that the surface of the object is divided into areas each being a diffuse reflection area or a specular reflection area.

[0045] In a preferred embodiment, the area dividing section performs the area division so that the surface of the object is divided into areas each being a specular reflection area, a diffuse reflection area, or a shaded area.

[0046] In a preferred embodiment, the area dividing section performs the area division so that it is divided into areas each being a specular reflection area, a diffuse reflection area, an attached shadow area, or a cast shadow area.

[0047] An image processing system of the present invention is an image processing system comprising an illumination device and an area dividing device for capturing an image of an object and thereby performing an optical area division of a surface of the object, the illumination device comprising: an illumination section for emitting linearly-polarized light onto the object; and an illumination control section for changing a polarization state of the linearly-polarized light of the illumination section, the area dividing device comprising: a polarization image capturing section for obtaining a polarization image of the object by receiving light having passed through a three-way or more polarizer having different polarization main axis angles; and a captured image determination section for comparing a polarization image captured in a past by the polarization image capturing section with a currently-captured polarization image to thereby determine whether the captured polarization states have changed sufficiently; a polarization information obtaining section for generating, from the obtained polarization image, polarization information for received polarized light by using a correspondence with a brightness of the light having passed through the three-way or more polarizer, for each of unit pixels of the polarization image; a light source dependency estimation section for estimating a light source dependency information by making a comparison between the polarization information generated by the polarization information obtaining section when it is determined by the captured image determination section that the polarization state of the illumination section has been changed by the illumination control section; and an area dividing section for performing the area division by using the polarization information generated by the polarization information obtaining section and light source variation information estimated by the light source dependency estimation section.

[0048] Another image processing system of the present invention is an area dividing system comprising an illumination device and an area dividing device for capturing an image of an object and thereby performing an optical area division of a surface of the object, the illumination device comprising: an illumination section for emitting linearly-polarized light onto the object; an illumination control section for changing a polarization state of the linearly-polarized light of the illumination section; and a communication section for transmitting a signal indicating a light emission to the area dividing device and receiving a signal indicating a completion of image-capturing from the area dividing device, the area dividing device comprising: a communication section for receiving a signal indicating a light emission from the illumination device and transmitting a signal indicating a completion of image-capturing to the illumination device; a polarization image capturing section for obtaining a polarization image of the object by receiving light having passed through a three-

way or more polarizer having different polarization main axis angles; a captured image determination section for comparing a polarization image captured in a past by the polarization image capturing section with a currently-captured polarization image to thereby determine whether the captured polarization states have changed sufficiently; a polarization information obtaining section for generating, from the obtained polarization image, polarization information for received polarized light by using a correspondence with a brightness of the light having passed through the three-way or more polarizer, for each of unit pixels of the polarization image; a light source dependency estimation section for estimating light source dependency information by making a comparison between the polarization information generated by the polarization information obtaining section when it is determined by the captured image determination section that the polarization state of the illumination section has been changed by the illumination control section; and an area dividing section for performing the area division by using the polarization information generated by the polarization information obtaining section and light source variation information estimated by the light source dependency estimation section.

[0049] An area dividing method of the present invention is an area dividing method for capturing an image of an object and thereby performing an optical area division of a surface of the object, comprising: an illumination step of emitting linearly-polarized light onto the object; an illumination control step of changing a polarization state of the linearly-polarized light of the illumination section; a polarization image capturing step of obtaining a polarization image of the object by receiving light having passed through a three-way or more polarizer having different polarization main axis angles; a polarization information obtaining step of generating, from the obtained polarization image, polarization, information for received polarized light by using a correspondence with a brightness of the light having passed through the three-way or more polarizer, for each of unit pixels of the polarization image; a control step of synchronizing the illumination control step with the polarization image capturing step; a light source dependency estimation step of estimating light source dependency information by making a comparison between the polarization information generated by the polarization information obtaining step when the polarization state of the illumination step is changed by the illumination control step; and an area dividing step of performing the area division by using the polarization information generated by the polarization information obtaining step and light source variation information estimated by the light source dependency estimation step.

[0050] A program of the present invention is a program for an area dividing device for capturing an image of an object and thereby performing an optical area division of a surface of the object, wherein the program instructs a computer to perform steps included in the area dividing method set forth above.

[0051] A model-based image synthesis device of the present invention is a model-based image synthesis device comprising a parameter estimation device and an image synthesis apparatus for synthesizing an image using a reflection model, the parameter estimation device comprising: an image capturing section for capturing an image of an object; an area dividing section for performing an optical area division of an image captured by the image capturing section according to the area dividing method set forth above; a light source information estimating section for estimating light source information regarding a light source illuminating the object; a shape information obtaining section for obtaining, as shape information, surface normal information or 3-dimensional position information of the object; a parameter estimation section for estimating a reflection model parameter by modeling the light source information estimated by the light source information estimating section for each area divided by the area dividing section and the shape information obtained by the shape information obtaining section, from the captured image of the object; a parameter database for storing the reflection parameter estimated by the parameter estimation section, the image synthesis apparatus comprising: a viewpoint/light source information obtaining section for obtaining a viewpoint or light source information of an image to be synthesized; and a rendering section for synthesizing an image according to the viewpoint or light source information obtained by the viewpoint/light source information obtaining section by using the reflection parameter information stored in the parameter database.

[0052] A model-based image synthesis method of the present invention is a model-based image synthesis method comprising a parameter estimation step and an image synthesis method step for synthesizing an image using a reflection model, the parameter estimation step comprising: an image capturing step of capturing an image of an object; an area dividing step of performing an optical area division of an image captured by the image capturing section according to the area dividing method set forth above; a light source information estimating step of estimating light source information regarding a light source illuminating the object; a shape information obtaining step of obtaining, as shape information, surface normal information or 3-dimensional position information of the object; and a parameter estimation step of estimating a reflection model parameter by modeling the light source information estimated by the light source information estimating section for each area divided by the area dividing section and the shape information obtained by the shape information obtaining section, from the captured image of the object, the image synthesis step comprising: a viewpoint/light source information obtaining step of obtaining a viewpoint or light source information of an image to be synthesized; and a rendering step of synthesizing an image according to the viewpoint or light source information obtained by the viewpoint/light source information obtaining section by using reflection parameter information estimated by the shape information obtaining step.

ADVANTAGEOUS EFFECTS OF INVENTION

[0053] With an image process of the present invention, it is possible to accurately separate a specular reflection area and a diffuse reflection area from each other by using two kinds of information, i.e., the light source condition dependency and the polarization information. Moreover, it is possible to synthesize an image faithful to the object by applying the area division based on the two kinds of information, i.e., the light source condition dependency and the polarization information, to the parameter estimation of a model-based image synthesis method.

BRIEF DESCRIPTION OF DRAWINGS

[0054] [FIG. **1**] A block diagram of an area dividing device according to a first embodiment of the present invention.

[0055] [FIG. **2**] A flow chart showing the flow of the process of an area dividing method according to the first embodiment of the present invention.

[0056] [FIG. **3**] A diagram showing an exemplary configuration of a camera including therein an area dividing device according to the first embodiment of the present invention.

[0057] [FIG. **4**] A schematic diagram showing a relationship between a patterned polarizer and an image sensor of an image capture device of the present invention.

[0058] [FIG. **5**] A schematic diagram illustrating an arrangement of the patterned polarizer of the present invention.

[0059] [FIG. **6**] A schematic diagram illustrating the sinusoidal brightness change and the observed brightness points of the present invention.

[0060] [FIG. **7**] An image captured of the object being a spherical globe, and degree of polarization ρ**1**, the polarization phase φmax**1** and the polarization estimation error E**1** obtained from that image.

[0061] [FIG. **8**] Schematic diagrams showing an image captured of the object being a spherical globe, and the degree of polarization ρ**1**, the polarization phase φmax**1** and the polarization estimation error E**1** obtained from that image.

[0062] [FIG. **9**] A diagram showing the image of FIG. **7** divided into a plurality of areas based on the high/low of the brightness.

[0063] [FIG. **10**] An image captured of the object being a styrene-foam head model, and the degree of polarization ρ**1**, the polarization phase φmax**1** and the polarization estimation error E**1** obtained from that image.

[0064] [FIG. **11**] An image captured of the object being a spherical globe, with the polarization state of the light source being different from that of FIG. **7**, and the degree of polarization ρ**2**, the polarization phase φmax**2** and the polarization estimation error E**2** obtained from that image.

[0065] [FIG. **12**] Schematic diagrams showing an image captured, of the object being a spherical globe, with the polarization state of the light source being different from that of FIG. **7**, and the degree of polarization ρ**2**, the polarization phase φmax**2** and the polarization estimation error E**2** obtained from that image.

[0066] [FIG. **13**] A diagram showing the image of FIG. **11** divided into a plurality of areas based on the high/low of the brightness.

[0067] [FIG. **14**] A schematic diagram showing, as an image, polarization phase difference values obtained by a light source dependency estimation section according to the first embodiment of the present invention.

[0068] [FIG. **15**] A schematic diagram illustrating the polarization phase difference.

[0069] [FIG. **16**] A table showing an area division criterion for an area dividing section according to the first embodiment of the present invention.

[0070] [FIG. **17**] A flow chart showing the flow of a process performed by the area dividing section according to the first embodiment of the present invention.

[0071] [FIG. **18**] A flow chart showing the flow of another process performed by the area dividing section according to the first embodiment of the present invention.

[0072] [FIG. **19**] A flow chart showing the flow of another process performed by the area dividing section according to the first embodiment of the present invention.

[0073] [FIG. **20**] An image captured of a billiard ball being the object, and schematic views thereof.

[0074] [FIG. **21**] A system diagram showing the shooting conditions for the area dividing device according to the first embodiment of the present invention.

[0075] [FIG. **22**] Views showing intermediate results of a process of the area dividing method according to the first embodiment of the present invention.

[0076] [FIG. **23**] A diagram showing the image of FIG. **22** divided into a plurality of areas based on the high/low of the brightness.

[0077] [FIG. **24**] Schematic diagrams showing intermediate results of a process of the area dividing method according to the first embodiment of the present invention.

[0078] [FIG. **25**] Views showing results of the process of the area dividing method according to the first embodiment of the present invention.

[0079] [FIG. **26**] Views showing results of another process of the area dividing method according to the first embodiment of the present invention.

[0080] [FIG. **27**] Another system diagram showing the shooting conditions for the area dividing device according to the first embodiment of the present invention.

[0081] [FIG. **28**] A diagram showing another exemplary configuration of a camera including therein an area dividing device according to the first embodiment of the present invention.

[0082] [FIG. **29**] A table showing another area division criterion for the area dividing section according to the first embodiment of the present invention.

[0083] [FIG. **30**] A flow chart showing the flow of another process performed by the area dividing section according to the first embodiment of the present invention.

[0084] [FIG. **31**] A block diagram of an area dividing device according to a second embodiment of the present invention.

[0085] [FIG. **32**] A flow chart showing the flow of the process of an area dividing method according to the second embodiment of the present invention.

[0086] [FIG. **33**] A diagram showing an exemplary configuration of a camera including therein an area dividing device according to the second embodiment of the present invention.

[0087] [FIG. **34**] A diagram showing an exemplary configuration of a camera including therein an area dividing device according to the second embodiment of the present invention.

[0088] [FIG. **35**] A system diagram showing the shooting conditions for the area dividing device according to the second embodiment of the present invention.

[0089] [FIG. **36**] Another system diagram showing the shooting conditions for the area dividing device according to the second embodiment of the present invention.

[0090] [FIG. **37**] Views showing intermediate results of a process of the area dividing method according to the second embodiment of the present invention.

[0091] [FIG. **38**] Schematic diagrams showing intermediate results of a process of the area dividing method according to the second embodiment of the present invention.

[0092] [FIG. **39**] A diagram showing the image of FIG. **37** divided into a plurality of areas based on the high/low of the brightness.

[0093] [FIG. **40**] A schematic diagram showing the positional relationship between light emitting devices and an image capture device in the area dividing device according to the second embodiment of the present invention.

[0094] [FIG. **41**] Views showing results of the process of the area dividing method according to the second embodiment of the present invention.

[0095] [FIG. **42**] Views showing results of another process of the area dividing method according to the second embodiment of the present invention.

[0096] [FIG. **43**] A table showing an area division criterion, including a shaded area, for the area dividing section according to the second embodiment of the present invention.

[0097] [FIG. **44**] A flow chart showing the flow of a process performed by the area dividing section, which performs an area division including shaded areas, according to the second embodiment of the present invention.

[0098] [FIG. **45**] A schematic diagram illustrating the shading classification into an attached shadow and a cast shadow.

[0099] [FIG. **46**] A schematic diagram illustrating how multiple reflection light is incident on an attached shadow area.

[0100] [FIG. **47**] A schematic diagram illustrating how multiple reflection light is incident on an cast shadow area.

[0101] [FIG. **48**] A table showing an area division criterion, including an attached shadow and a cast shadow, for the area dividing section according to the second embodiment of the present invention.

[0102] [FIG. **49**] A flow chart showing the flow of a process performed by the area dividing section, which performs an area division including an attached shadow and a cast shadow, according to the second embodiment of the present invention.

[0103] [FIG. **50**] A table showing another area division criterion, including an attached shadow and a cast shadow, for the area dividing section according to the second embodiment of the present invention.

[0104] [FIG. **51**] A flow chart showing the flow of another process performed by the area dividing section, which performs an area division including an attached shadow and a cast shadow, for the second embodiment of the present invention.

[0105] [FIG. **52**] A block diagram showing an area dividing system according to a third embodiment of the present invention.

[0106] [FIG. **53**] A flow chart showing the flow of a process of an area dividing method according to the third embodiment of the present invention.

[0107] [FIG. **54**] A diagram showing an exemplary configuration of a camera including therein an area dividing device and a light emitting device according to the third embodiment of the present invention.

[0108] [FIG. **55**] A flow chart showing the flow of the process of an area dividing method according to the third embodiment of the present invention.

[0109] [FIG. **56**] Another block diagram showing the area dividing system according to the third embodiment of the present invention.

[0110] [FIG. **57**] A flow chart showing the flow of another process of the area dividing method according to the third embodiment of the present invention.

[0111] [FIG. **58**] A diagram showing another exemplary configuration of a camera including therein an area dividing device and a light emitting device according to the third embodiment of the present invention.

[0112] [FIG. **59**] A block diagram showing a configuration of an image synthesis apparatus according to one embodiment of the present invention.

[0113] [FIG. **60**] A flow chart showing the flow of a process of a parameter estimation method in an image synthesis method according to one embodiment of the present invention.

[0114] [FIG. **61**] A flow chart showing the flow of a process of an image synthesis estimation method in an image synthesis method according to one embodiment of the present invention.

[0115] [FIG. **62**] A diagram showing an exemplary configuration of a camera including therein an image synthesis apparatus of the present invention.

[0116] [FIG. **63**] A schematic diagram illustrating a light source estimation method utilizing a mirrored ball.

[0117] [FIG. **64**] A schematic diagram illustrating the relationship between the normal direction vector, the viewing vector and the light source direction vector.

[0118] [FIG. **65**] A schematic diagram illustrating the constant Sr for expressing the difference in the luminance value between the diffuse reflection component and the specular reflection component.

[0119] [FIG. **66**] A chart showing the flow of a specular reflection image parameter estimation process in an image synthesis process according to one embodiment of the present invention.

[0120] [FIG. **67**] A conceptual diagram illustrating various parameters of an expression representing the incident illuminance.

[0121] [FIG. **68**] A flow chart showing the flow of a parameter estimation process by a simplex method.

[0122] [FIG. **69**] A flow chart showing the flow of a parameter updating process in a simplex method.

[0123] [FIG. **70**] A schematic graph showing BRDF obtained by using the area dividing device according to the first embodiment of the present invention.

[0124] [FIG. **71**] A schematic table showing model parameters stored in a parameter DB for an image synthesis process according to one embodiment of the present invention.

[0125] [FIG. **72**] A graph showing the degree of polarization of the specular reflection component with respect to the angle of incidence for objects whose refractive indices are n=1.1, 1.3, 1.5 and 2.0.

[0126] [FIG. **73**] A graph showing the degree of polarization of the diffuse reflection component with respect to the emittance angle for objects whose refractive indices are n=1.1, 1.3, 1.5 and 2.0.

[0127] [FIG. **74**] Views showing the specular reflection area and the diffuse reflection area divided by a conventional area division.

[0128] [FIG. **75**] A schematic graph showing BRDF obtained in order to illustrate problems of a conventional method.

[0129] [FIG. **76**] A synthesized image produced by using a conventional area dividing approach.

DESCRIPTION OF EMBODIMENTS

[0130] Embodiments of the present invention will now be described with reference to the drawings.

First Embodiment

[0131] First, the outline of an image processing apparatus according to a first embodiment of the present invention will be described. The image processing apparatus of the present embodiment calculates the light source dependency by

changing the polarization state of the illumination section (light source). An area division of the object is performed by using the polarization information and the light source dependency resulting from the change of the polarization state.

[0132] FIG. **1** is a block diagram showing the image processing apparatus of the present embodiment. The image processing apparatus is an apparatus for capturing an image of the object and thereby dividing (performing an area division of) the surface of the object into a plurality of areas of different optical properties.

[0133] The image processing apparatus includes: an illumination unit **121** for emitting linearly-polarized light onto the object while changing the polarization state thereof; a polarization information obtaining section **122** for obtaining polarization information of the object; a control section **120** for performing a synchronization operation between the illumination unit **121** and the polarization information obtaining section **122**; a light source dependency estimation section **105** for estimating light source dependency information by making a comparison between different polarization information generated by the polarization information obtaining section **122** when the polarization state (the polarization main axis direction of the linearly-polarized light in the present embodiment) is changed by the illumination unit **121**; and an area dividing section **106** for performing an area division by using the polarization information generated by the polarization information obtaining section **122** and the light source variation information estimated by the dependency estimation section **105**.

[0134] The illumination unit **121** includes an illumination section **101** for emitting linearly-polarized light onto the object, and an illumination control section **102** for changing the polarization state of the linearly-polarized light of the illumination section **101**. The polarization information obtaining section **122** includes a polarization image capturing section **103** for obtaining a polarization image of the object, and a polarization information obtaining section **104** for generating the polarization information, which is information regarding the received polarized light. The polarization image capturing section **103** obtains the polarization image of the object by receiving light having passed through a three-way or more polarizer having different polarization main axis angles. From the obtained polarization image, the polarization information obtaining section **104** generates the polarization information, which is information regarding the received polarized light, by using the correspondence with the brightness of the light having passed through the three-way or more polarizer, for each of unit pixels of the polarization image.

[0135] FIG. **2** is a flow chart showing the flow of the process of an area dividing method of the present embodiment. In step S**101** of FIG. **2**, the illumination section **101** emits polarized light which is polarized in a main axis direction specified by the illumination control section **102** onto the object. In step S**102**, the polarization image capturing section **103** receives light, by means of an image sensor, from the object through a patterned polarizer to be described later, thus obtaining a first polarization image, which is an image including polarization information. This is achieved by the control section **120** synchronizing the illumination unit **121** and the polarization information obtaining section **122** with each other.

[0136] The patterned polarizer has three or more polarization main axis angles as will be described later. In step S**103**, the polarization information obtaining section **104** generates the polarization information, which is information regarding the received polarized light, by using the correspondence with the brightness of the light having passed through the three-way or more polarizer, for each of unit pixels of the captured first polarization image.

[0137] In step S**104**, the illumination control section **102** controls the illumination section **101** so as to vary the main axis direction of the linearly-polarized light of the illumination section **101** so that the illumination section **101** emits polarized light of a different polarization state from that of step S**101** onto the object. In step S**105**, the polarization image capturing section **103** again receives light, by means of an image sensor, from the object through a patterned polarizer **201**, thus obtaining a second polarization image. This is achieved by the control section **120** synchronizing the illumination unit **121** and the polarization information obtaining section **122** with each other.

[0138] The first polarization image and the second polarization image are polarization images for different main axis directions of the linearly-polarized light from the illumination section **101**. In step S**106**, the polarization information obtaining section **104** again generates the polarization information, which is information regarding the received polarized light, by using the correspondence with the brightness of the light having passed through the three-way or more polarizer, for each of unit pixels of the captured second polarization image.

[0139] In step S**107**, the light source dependency estimation section **105** estimates the light source dependency by making a comparison between the polarization information obtained by the polarization information obtaining section **104** from the first polarization image and the second polarization image. In step S**108**, the area dividing section **106** performs an area division by using the polarization information generated by the polarization information obtaining section **104** and the light source dependency information estimated by the light source dependency estimation section **105**.

[0140] It is assumed herein that the illumination control section **102**, the polarization image capturing section **103**, the polarization information obtaining section **104**, the light source dependency estimation section **105**, the area dividing section **106** and the control section **120** are implemented by a CPU **204** executing a program. Note however that some or all of these functions may be implemented by hardware. A memory **203** stores a polarization image captured by the polarization image capturing section **103**, polarization information obtained by the polarization information obtaining section **104**, and light source dependency information estimated by the light source dependency estimation section **105**.

[0141] Next, referring to FIG. **3**, a configuration and an operation of a camera including therein the image processing apparatus of the present embodiment will be described. FIG. **3** is a block diagram showing an exemplary configuration of such a camera. The camera of FIG. **3** includes the patterned polarizer **201**, an image capture device **202**, the memory **203**, the CPU **204**, an illumination control device **208**, a light emitting device **207**, a rotation mechanism **206**, and a polarizer **205**.

[0142] In step S**101**, polarized light is emitted onto the object from the camera of FIG. **3**. Where a flash is used as the light emitting device **207**, since a polarization filter (the polarizer **205**) is provided in front of the flash, polarized light can be emitted onto the object. As means for using polarized light, a liquid crystal polarizer, or the like, may be used.

[0143] The polarizer **205** is rotated by the rotation mechanism **206**. The illumination control section **102** changes the main axis direction of the polarized light by controlling the rotation mechanism **206**. Where a liquid crystal polarizer is used as the polarizer, instead of using a polarization filter, the illumination control section **102** changes the main axis direction of the polarized light by changing the voltage applied to the liquid crystal polarizer.

[0144] An operation of the camera having such a configuration as shown in FIG. **3** will now be described in detail.

[0145] First, in step S**101** shown in FIG. **2**, the illumination section **101** of FIG. **1** uses the light emitting device **207** and the polarizer **205** to thereby emit polarized light which is polarized in a main axis direction specified by the illumination control section **102** onto the object. Where the flash of the camera is used as the light emitting device **207**, for example, this can be realized by providing a polarization filter (the polarizer **205**) in front of the flash. A liquid crystal polarizer, or the like, may be used as means for using polarized light.

[0146] The polarizer **205** is rotated by the rotation mechanism **206**. The illumination control section **102** changes the main axis direction of the polarized light by controlling the rotation mechanism **206**. Where a liquid crystal polarizer is used as the polarizer, instead of using a polarization filter, the illumination control section **102** may vary the main axis direction of the polarized light by changing the voltage applied to the liquid crystal polarizer.

[0147] In step S**102**, the polarization image capturing section **103** receives light, by means of the image capture device **202**, from the object through the patterned polarizer **201**, thus obtaining a first polarization image, which is an image including polarization information. This is achieved by the CPU **120** synchronizing the light emission by the light emitting device **207**, the rotation of the polarizer **205** by the rotation mechanism **206**, and the image-capturing by the image capture device **202** with one another.

[0148] FIG. **4** is a schematic diagram showing the relationship between the patterned polarizer **201** and the image capture device **202** included in the polarization image capturing section **103** shown in FIG. **1**. In the present embodiment, the patterned polarizer **201** is laid on the image capture device **202**. It is preferred that the patterned polarizer **201** is provided in parallel to the image-capturing plane of the image capture device **202**. The incident light passes through the patterned polarizer **201** to reach the image sensor **202**, where the brightness thereof is observed, and therefore the polarization image capturing section **103** can obtain the polarization information.

[0149] FIG. **5** shows the four-way patterned polarizer, wherein straight lines in each pixel represent the polarization main axis direction of the minute polarizing plate provided on the pixel. That is, the image capture device includes pixels of four different polarization directions defined by the rotation angles (Φi=0°, 45°, 90° and 135°) of the polarization axis. The patterned polarizer exhibits polarization characteristics such that the TM-wave is transmitted and the TE-wave is reflected (not transmitted).

[0150] Such characteristics can be produced by, for example, using a photonic crystal described in Kawashima, Sato, Kawakami, Nagashima, Ota, Aoki, "Development polarization imaging device and applications by using patterned polarizer", Proceedings of the IEICE General Conference 2006, No. D-11-52, P. 52, 2006. With a photonic crystal, the TE-wave is light that has the vibration plane parallel to grooves formed on the surface and the TM-wave is light that has the vibration plane perpendicular thereto. When capturing this polarization image, it is preferred that the dynamic range of the brightness and the number of bits are as large as possible (e.g., 16 bits).

[0151] In step S**103** of FIG. **2**, the polarization information obtaining section **104** generates the polarization information, which is information regarding the received polarized light, by using the correspondence with the brightness of the light having passed through the three-way or more polarizer, for each of unit pixels of the first polarization image. This process will now be described in detail.

[0152] It is known in the art that the brightness of light having passed through a polarizer (linearly-polarized light which is polarized in the polarization main axis direction) changes depending on the polarization main axis angle of the polarizer. FIG. **6** shows how a single sinusoidal curve is formed by the brightnesses **401** to **404** of light having passed through four different polarizers having different polarization main axis angles ϕi=0°, 45°, 90° and 135°. The sinusoidal curve represents the polarization characteristics at the point **501** in FIG. **5**. Herein, FIG. **5** is a schematic diagram showing the four-way polarizer **201** and the image sensor **202** of FIG. **4** as viewed from the direction of the incident light.

[0153] Note that the polarization main axis angle being 0° is equal to that being 180° (n). When obtaining the sinusoidal curve, it is preferred that a camera such that the shooting gamma=1 is used or alinearity correction is made so that the shooting gamma=1. While the four points are shown to be closely along the single sinusoidal curve, in fact, a single sinusoidal function with a 180-degree cycle is determined, as an optimal value, from many measured points.

[0154] The polarization information obtaining section **104** generates, as the polarization information, the amplitude and the phase information of the curve. Specifically, the reflected light brightness I for the main axis angle ϕ of the patterned polarizer is approximated as follows.

[Exp. 1]

$$I(\phi)=A\cdot\sin 2(\phi-B)+C \qquad \text{Expression 1}$$

[0155] Herein, as shown in FIGS. **6**, A, B and C are constants that represent the amplitude, the phase and the average value, respectively, of the brightness fluctuation curve due to the polarizer. Now, Expression 1 can be developed as follows.

[Exp. 2]

$$I(\phi)=a\cdot\sin 2\phi+b\cdot\cos 2\phi+C \qquad \text{Expression 2}$$

[0156] where

[Exp. 3]

$$A=\sqrt{a^2+b^2}, \qquad \text{Expression 3}$$

$$\sin(-2B)=\frac{b}{\sqrt{a^2+b^2}},$$

$$\cos(-2B)=\frac{a}{\sqrt{a^2+b^2}}$$

[Exp. 4]

$$B=-\frac{1}{2}\tan^{-1}\left(\frac{b}{a}\right) \qquad \text{Expression 4}$$

[0157] That is, for a 4-pixel sample (ϕ_i I_i), the sinusoidal function, Expression 1, can be approximated by obtaining A, B and C that minimize Expression 5 below. Note that I_i represents the measured brightness for the polarizing plate rotation angle ϕ_i. N is the number of samples, which is 4 here.

[Exp. 5]

$$f(a, b, C) = \sum_{i=1}^{N} (I_i - a \cdot \sin 2\phi_i - b\cos 2\phi_i - C)^2 \quad \text{Expression 5}$$

[0158] Through the above process, the three parameters A, B and C of the sinusoidal approximation are determined. By using the parameters obtained as described above, the polarization information obtaining section **104** obtains at least one of the degree of polarization ρ, the polarization phase φmax, the polarization estimation error E, the polarization maximum luminance value Imax, and the polarization minimum luminance value Imin, as the polarization information.

[0159] Degree of polarization ρ

[Exp. 6]

$$\rho = \frac{I_{max} - I_{min}}{I_{max} + I_{min}} = \frac{A}{C} = \frac{A}{I} \quad \text{Expression 6}$$

[0160] Polarization phase φmax ($0 \leqq \phi max \leqq \pi$ [rad])

Expression 7

$$\phi_{max} = \frac{\pi}{4} + B \quad \text{[Exp. 7]}$$

[0161] Polarization estimation error E

Expression 8

$$E = \sum_{i=0}^{N-1} (I_i - A \cdot \sin 2(\psi_i - B) - C)^2 \quad \text{[Exp. 8]}$$

[0162] Polarization maximum luminance value Imax

[Exp. 9]

$$I_{max} = A + C \quad \text{Expression 9}$$

[0163] Polarization minimum luminance value Imin

[Exp. 10]

$$I_{min} = C - A \quad \text{Expression 10}$$

[0164] Herein, the degree of polarization is an index representing how much the light is polarized, and the polarization phase is the angle at which the brightness, which changes depending on the polarization main axis angle, is maximized. The polarization estimation error is the total difference between the brightness measured for a 4-pixel sample and the brightness determined from the above sinusoidal function obtained by approximation. The polarization maximum luminance value is the maximum luminance value which can be reached as the main axis angle φ of the patterned polarizer is changed, and the polarization minimum luminance value is the minimum luminance value which can be reached as the main axis angle φ of the patterned polarizer is changed, and is a non-polarized component luminance value.

[0165] FIG. **7** shows, each as an image, the degree of polarization ρ**1**, the polarization phase φmax**1** and the polarization estimation error E**1**, which are obtained from the first polarization image for the spherical globe. In this figure, FIG. **7**(*a*) shows an image of the globe, which is the object, FIG. **7**(*b*) the degree of polarization ρ**1** for the object of FIG. **7**(*a*), FIG. **7**(*c*) the polarization phase φmax**1** (0° being black, and 180° being white) for the object of FIG. **7**(*a*), and FIG. **7**(*d*) the polarization estimation error E**1** for the object of FIG. **7**(*a*). FIG. **8** shows the images of FIG. **7** in a schematic manner (with shading emphasized). In the figure, areas (A**01** to D**04**) correspond to the areas in FIG. **9**. FIG. **9** shows views obtained by dividing each image of FIG. **7** into a plurality of areas based on the high/low of the brightness. In any image, the higher the brightness is (the whiter), the larger the value.

[0166] FIG. **10** shows the result of a similar process performed for a styrene-foam head model. From these images, it can be seen that the degree of polarization is high near the occluding edge, and that the polarization phase monotonously increases clockwise around the sphere with a 180° cycle in areas that are not covered by the shade of the object. These polarization information images are deeply related to the direction of the surface normal of the object, and provide a basis for shape estimation.

[0167] In FIGS. **7**(*h*) to **7**(*d*), data of the background area (Ba**01** to Ba**04**) are disturbed. This is because the brightness resolution was low in the background area since it was very dark therein. Therefore, the reliability of the polarization information is decreased, and the data is disturbed. By increasing the brightness of the background area by elongating the exposure time, it is possible to obtain polarization information of a sufficient precision even in the background area. The background area may be masked so that it is excluded from the area dividing process.

[0168] In step S**104**, the illumination control section **102** controls the illumination section **101** so as to emit, onto the object, polarized light whose polarization state is different from that when the first polarization image was obtained. The illumination section **101** again emits polarized light which is polarized in a main axis direction specified by the illumination control section **102** onto the object.

[0169] The change of the polarization state in this process is to vary the direction of the polarization main axis, for example. The illumination control section **102** may rotate the polarization main axis direction by 90 degrees, for example.

[0170] In step S**105**, the polarization image capturing section **103** receives light, by means of an image sensor, from the object through the patterned polarizer **201**, as described above, thus obtaining a second polarization image, which is an image including polarization information. This is achieved by the control section **120** synchronizing the illumination unit **121** and the polarization information obtaining section **122** with each other. Where polarized light of varied polarization information are emitted at intervals of 0.2 sec by the control section **120**, for example, the control section **120** may be used to synchronize the image-capturing in step S**102** by the polarization image capturing section **103** with the emission of polarized light, and to set the interval from step S**102** to the image-capturing in step S**105** to be 0.2 sec. Then, the user can

obtain two images, i.e., the first polarization image and the second polarization image, in a single image-capturing operation.

[0171] In step S**106**, the polarization information obtaining section **104** generates polarization information, which is information regarding the received polarized light, by using the correspondence with the brightness of the light having passed through the three-way or more polarizer, as described above, for each of unit pixels of the captured second polarization image.

[0172] FIG. **11** shows, each as an image, the degree of polarization ρ**2**, the polarization phase φmax**2** and the polarization estimation error E**2**, which are obtained from the second polarization image. In this figure, FIG. **11**(*a*) shows an image of the globe, which is the object, FIG. **11**(*b*) the degree of polarization ρ**2** for the object of FIG. **11**(*a*), FIG. **11**(*c*) the polarization phase φmax**2** (0° being black, and 180° being white) for the object of FIG. **11**(*a*), and FIG. **11**(*d*) the polarization estimation error E**2** for the object of FIG. **11**(*a*). FIG. **12** shows the images of FIG. **11** in a schematic manner (with shading emphasized). In the figure, areas (A**11** to D**14**) correspond to areas (A**11** to D**14**) in FIG. **13**. FIG. **13** shows views obtained by dividing each image of FIG. **11** into a plurality of areas based on the high/low of the brightness. In any image, the higher the brightness is (the whiter), the larger the value.

[0173] In step S**107** of FIG. **2**, the light source dependency estimation section **105** estimates the light source dependency by making a comparison between the polarization information obtained by the polarization information obtaining section **104** from the first polarization image and the second polarization image. This process will now be described in detail.

[0174] As described above, the specular reflection area and the diffuse reflection area are different from each other in terms of the light source dependency. In the present embodiment, the polarization axis direction of the emitted light is changed in order to examine the light source dependency. As described above, the illumination control section **102** is used to emit linearly-polarized light whose polarization axis directions are different from each other by 90 degrees, thereby obtaining the first polarization image and the second polarization image. The light source dependency is estimated by making a comparison between polarization phase information obtained from these images. Note that as is clear from a comparison between FIGS. **7** and **11**, the degree of polarization ρ**1** and the degree of polarization ρ**2** are generally of the same magnitude (the same brightness) in the area B**12**. It is believed that this is because even though the polarized light emitted onto the object have polarization main axis angles different from each other, the brightnesses of the polarized light reflected in the specular reflection area by chance become substantially equal to each other.

[0175] FIG. **14** shows, as an image, the difference value between the polarization phase φmax**1** obtained from the first polarization image and the polarization phase φmax**2** obtained from the second polarization image. In this figure, pixels with higher brightnesses (whiter) represent those of larger difference values.

[0176] As described above, since the specular reflection area occurs by the surface reflection, the polarization characteristics of the incident light are maintained. That is, it can be considered that the specular reflection area has a high light source dependency. On the other hand, in the diffuse reflection area, due to the repeated scattering, the polarization characteristics of the incident light have been lost. That is, it can be considered that the diffuse reflection area has a low light source dependency as it is not influenced by the incident light.

[0177] In view of this, the light source dependency estimation section **105** estimates, as the light source dependency, the first light source dependency LDφ according to the following expression by using the polarization phase difference of pixels between the first polarization image and the second polarization image.

Expression 11

$$LD_{\varphi} = \frac{2}{\pi} \cdot |\varphi_{max1} - \varphi_{max2}| \qquad \text{[Exp. 11]}$$

[0178] Herein, $|\phi_{max1}-\phi_{max2}|$ is the difference value between the polarization phases φmax**1**[rad] and φmax**2**[rad] taking the period π into consideration, as expressed by the following expression. The range thereof is [0,π/2].

[Exp. 12]

$$|\phi_{max1}-\phi_{max2}|=\min(|\phi_{max}-\phi_{max2}|,\pi-|\phi_{max1}-\phi_{max2}|) \qquad \text{Expression 12}$$

[0179] FIG. **15** is a diagram showing the relationship between $|\phi_{max1}-\phi_{max2}|$ and φmax**1**, φmax**2**. The first light source dependency LDφ is 0 when the polarization phase of the first polarization image and that of the second polarization image are equal to each other, and the value increases as the polarization phase difference increases and is 1 when the polarization phase difference is at maximum (π/2). That is, the first light source dependency LDφ is larger when the polarization phase changes depending on the change of the polarization state of the light source, and the first light source dependency LDφ is small when the polarization phase is not influenced by the change of the polarization state of the light source.

[0180] The light source dependency does not need to be the polarization phase difference of pixels between the first polarization image and the second polarization image, but may be, for example, the second light source dependency LDρ, which is the difference in the degree of polarization between the first polarization image and the second polarization image. In such a case, the second light source dependency LDρ is expressed by the following expression.

[Exp. 13]

$$LD_{\rho}=|\rho_1-\rho_2| \qquad \text{Expression 13}$$

[0181] As is the first light source dependency LDφ, the second light source dependency LDρ is 1 when the degree of polarization of the first polarization image and that of the second polarization image are equal to each other, and the value increases as the difference in the degree of polarization increases and is 0 when the difference in the degree of polarization is at maximum (1.0). That is, the second light source dependency LDρ is large when the degree of polarization changes depending on the change of the polarization state of the light source, and the second light source dependency LDρ is small when the degree of polarization is not influenced by the change of the polarization state of the light source. Note that as described above, even though the polarized light emitted onto the object have polarization main axis angles differ-

ent from each other, the brightnesses of the light reflected in the specular reflection area may by chance become equal to each other. In order to avoid an erroneous determination which may occur in such a case, polarized light of three or more different polarization axis directions may be used to obtain three or more different polarization images, based on which the difference in the degree of polarization is evaluated.

[0182] In step S**108** of FIG. **2**, the area dividing section **106** performs an area division based on the polarization information generated by the polarization information obtaining section **104** and the light source dependency information estimated by the light source dependency estimation section **105**. This process will now be described in detail.

[0183] FIG. **16** shows an image division criterion for the area dividing section **106**. FIG. **17** is a flow chart showing the flow of a process performed by the area dividing section **106**. The flow of the process will now be described.

[0184] First, in step S**201** of FIG. **17**, in order to determine whether the pixel belongs to a non-polarized area or a polarized area, the area dividing section **106** compares the magnitude of the degree of polarization ρ**1** of the pixel with the threshold Thρ to determine whether the degree of polarization ρ is greater than or equal to the threshold Thρ or smaller than Thρ. If the degree of polarization ρ**1** of the pixel is smaller than the threshold Thρ (No in step S**201**), it is determined that the pixel is included in the diffuse reflection non-polarized area (step S**202**), and the process is ended. On the other hand, if the degree of polarization ρ**1** of the pixel is greater than or equal to the threshold Thρ (Yes in step S**201**), it is determined whether the first light source dependency LDϕ estimated by the light source dependency estimation section **105** is greater than the threshold Thϕ (step S**203**). If the first light source dependency LDϕ is greater than or equal to the threshold Thϕ (Yes in step S**203**), it is determined that the pixel is a specular reflection polarized area (step S**204**), and the process is ended. On the other hand, if the first light source dependency LDϕ is smaller than the threshold Thϕ (No in step S**203**), it is determined that the pixel is included in the diffuse reflection polarized area (step S**205**), and the process is ended.

[0185] The threshold Thρ of the degree of polarization may be set based on the refractive index of the object, the normal direction of the object, the light source direction, the viewing direction, etc. As shown in FIGS. **72** and **73**, the degree of polarization of the specular reflection component and the degree of polarization of the diffuse reflection component of the object can be determined uniquely once the refractive index, the angle of incidence and the emittance angle are obtained. Therefore, the degree of polarization of the specular reflection component and the degree of polarization of the diffuse reflection component, which are obtained from FIGS. **72** and **73**, may be used as Thρ. For example, if the refractive index of the object is 1.3 and the angle of incidence is 30 degrees, it is believed from FIG. **73** that the degree of polarization of the diffuse reflection component is certainly 0.05 or less, and therefore the threshold Thρ can be set to 0.05.

[0186] If information such as the refractive index of the object, the normal direction of the object, the light source direction, the viewing direction, etc., is not available, the threshold Thρ may be determined based on the maximum value of the degree of polarization of the diffuse reflection component. For example, assuming that there is no object whose refractive index is 2.0 or more, the maximum value of the degree of polarization of the diffuse reflection component is believed to be about 0.6 from FIG. **73**, and the threshold Thρ may therefore be set to be about 0.8.

[0187] The threshold Thϕ of the first light source dependency LDϕ may be determined experimentally, and may be set to 0.5, for example. The threshold Thρ of the degree of polarization may also be determined experimentally.

[0188] In step S**201**, the comparison may be made using the degree of polarization ρ**2** obtained from the second polarization image, instead of making the comparison using the degree of polarization ρ**1** obtained from the first polarization image. Also in such a case, the comparison may be made with the threshold Thρ. Alternatively, the average value between the degree of polarization ρ**1** obtained from the first polarization image and the degree of polarization ρ**2** obtained from the second polarization image may be used. For example, when the main axis of the linearly-polarized light of the light source is changed by 90 degrees, it is possible to obtain a degree of polarization that is substantially equivalent to that when a light source of a non-polarized component is used, by obtaining the average value between the degree of polarization ρ**1** and the degree of polarization ρ**2**. This allows for a more accurate area division. Also in such a case, the comparison may be made with the threshold Thρ.

[0189] In step S**201**, the comparison may be made using the polarization estimation error E**1** obtained from the first polarization image. This process is effective where there is a large error in the luminance value, e.g., where the stability of the light source is low. FIG. **18** is a flow chart showing the flow of the process performed by the area dividing section **106** in such a case. In FIG. **18**, like steps to those of FIG. **17** are denoted by like reference numerals to those of FIG. **17** and will not be described in detail below.

[0190] In step S**206** of FIG. **18**, the area dividing section **106** determines whether the magnitude of the polarization estimation error E**1** is greater than or equal to the threshold ThE or is less than the threshold ThE. If the polarization estimation error E**1** of the pixel is greater than or equal to the threshold ThE (No in step S**206**), it is determined that the pixel is a diffuse reflection non-polarized area (step S**202**), and the process is ended. On the other hand, if the polarization estimation error E**1** is less than the threshold ThE (Yes in step S**206**), a comparison is made as to whether the first light source dependency LDϕ estimated by the light source dependency estimation section **105** is greater than the threshold Thϕ (step S**203**).

[0191] In step S**203**, the second light source dependency LDρ, which is the difference in the degree of polarization between the first polarization image and the second polarization image described above, may be used. As the degree of polarization is strongly influenced by multiple reflection, or the like, it is effective to use the second light source dependency LDρ, which is the difference in the degree of polarization, for an object that is unlikely to be influenced by multiple reflection. Specifically, an object that is unlikely to be influenced by multiple reflection is an object having a convex shape. The first light source dependency LDϕ and the second light source dependency LDρ may be used as being combined with each other. In such a case, the weighted average between Expression 11 and Expression 13 can be obtained. By using the two polarization information as a combination, it is possible to realize a robust area division.

[0192] FIG. **19** is a flow chart showing the flow of the process performed by the area dividing section **106** in such a

case. In FIG. **19**, like steps to those of FIG. **17** are denoted by like reference numerals to those of FIG. **17** and will not be described in detail below. In step S**207**, if the second light source dependency LDρ is greater than or equal to the threshold Thρ (Yes in step S**207**), it is determined that the pixel is a specular reflection polarized area (step S**204**), and the process is ended. On the other hand, if the second light source dependency LDρ is smaller than the threshold Thρ (No in step S**207**), it is determined that the pixel is a diffuse reflection polarized area (step S**205**), and the process is ended.

[0193] The threshold Thρ of the second light source dependency LDρ may be determined experimentally, and may be set to 0.2, for example.

[0194] FIGS. **20**, **22** to **26** show results of performing the area division of the present embodiment. FIG. **21** is a diagram showing the shooting conditions for the area division of the present embodiment.

[0195] As shown in FIG. **21**, the light emitting device **207** is provided near the image capture device **202**, and the main axis direction of the polarizer is changed by 90 degrees by the rotation mechanism **206**. FIG. **20**(*a*) shows a billiard ball being the object. FIG. **20**(*b*) is the image of the surface of the billiard ball shown in FIG. **20**(*a*), in which the area of white pixels is labeled with reference numeral "B**21**", and the remaining area with reference numeral "A**21**". FIG. **20**(*c*) shows FIG. **20**(*b*) in a schematic manner (with shading emphasized). In this figure, the areas A**21** and B**21** correspond to the areas A**21** and B**21** of FIG. **20**(*b*), respectively.

[0196] FIG. **22** shows polarization information obtained by the polarization information obtaining section **104** when the main axis direction of the polarized light is changed between the horizontal direction and the vertical direction by the illumination control section **102**, with the billiard ball shown in FIG. **20**(*a*) being the object. FIG. **22**(*a*) shows the degree of polarization ρ**1** obtained from the first polarization image which is captured with the main axis direction of the polarized light being in the horizontal direction, FIG. **22**(*b*) shows the polarization phase φmax**1** obtained from the first polarization image, FIG. **22**(*c*) shows the degree of polarization ρ**2** obtained from the second polarization image which is captured with the main axis direction of the polarized light being in the vertical direction, FIG. **22**(*d*) shows the polarization phase φmax**2** obtained from the second polarization image, and FIG. **22**(*e*) shows the first light source dependency LDφ obtained from the polarization phases φmax**1** and φmax**2**.

[0197] Pixels of higher brightnesses in FIGS. **22**(*a*)-(*d*) indicate larger values of the degree of polarization ρ**1**, the polarization phase φmax**1**, the degree of polarization ρ**2** and the polarization phase φmax**2**, respectively. Note that in FIG. **22**(*e*), white represents the value of the first light source dependency LDφ being 1, and black represents the value being 0.

[0198] FIG. **23** shows views obtained by dividing each image of FIG. **22** into a plurality of areas based on the high/low of the brightness. FIG. **24** shows the images of FIG. **22** in a schematic manner (with shading emphasized). In the figure, areas (A**31** to D**35**) correspond to the areas in FIG. **23**. FIG. **25** shows results of performing the area division of the present embodiment by using the polarization information of FIG. **22**. FIG. **25**(*a*) shows pixels where the degree of polarization ρ**1** for the first polarization image is greater than or equal to the threshold Thρ in step S**201**. FIGS. **25**(*b*), (*c*) and (*d*) show the "diffuse reflection non-polarized area", the "specular reflection polarized area" and the "diffuse reflection polarized area", respectively, as divided by the present embodiment. FIG. **25**(*e*) shows the "diffuse reflection area", which is the union of the diffuse reflection non-polarized area and the diffuse reflection polarized area. Each area of white pixels in FIG. **25** represents an area divided from the remaining area (area of black pixels).

[0199] With the conventional method of performing an area division based only on the degree of polarization, the white pixel area shown in FIG. **25**(*a*) will be assigned as the "specular reflection area" and the white pixel area shown in FIG. **25**(*b*) as the "diffuse reflection area", resulting in the area A (FIG. **25**(*a*)), which is near the occluding edge, being erroneously included in the specular reflection area, as described above, thereby causing a significant error in the extent of each divided area.

[0200] On the other hand, with the area dividing method of the present embodiment, where the light source dependency is used in addition to the polarization information, the white pixel area shown in FIG. **25**(*c*) is divided as the "specular reflection area" and the white pixel area shown in FIG. **25**(*e*) as the "diffuse reflection area". Thus, it is possible to perform an accurate area division as compared with the conventional method.

[0201] FIG. **26** shows results using the degree of polarization ρ**2** obtained from the second polarization image, instead of making a comparison by using the degree of polarization ρ**1** obtained from the first polarization image, in step S**201**. FIG. **26**(*a*) shows pixels where the degree of polarization ρ**2** for the second polarization image is greater than or equal to the threshold Thρ in step S**201**. FIGS. **26**(*b*), (*c*) and (*d*) show the "diffuse reflection non-polarized area", the "specular reflection polarized area" and the "diffuse reflection polarized area", respectively, as divided by the area division of the present embodiment. FIG. **26**(*e*) shows the "diffuse reflection area", which is the union of the diffuse reflection non-polarized area and the diffuse reflection polarized area. Each area of white pixels in FIG. **26** represents an area divided from the remaining area (area of black pixels).

[0202] As with the area dividing method described above with reference to FIG. **25**, using the degree of polarization ρ**2** for the second polarization image also makes it possible to perform a more accurate area division as compared with the conventional method since the polarization information and the light source dependency are both used.

[0203] A comparison between FIGS. **25** and **26** shows that an area B of white pixels is observed in FIG. **26**(*c*), whereas such an area B is not seen in FIG. **25**(*c*). The polarization state of light that is incident on and reflected by the surface of the object is influenced by the relationship between the polarization direction of the straight-line direction of incidence and the angle of incidence or the emittance angle, and the degree of polarization of reflected light of linearly-polarized light incident on the surface of an object may become high depending on the polarization direction. In such a case, a part of the "specular reflection area" may be determined erroneously for such pixels that give reflected light of a high degree of polarization. In order to reliably prevent such an erroneous determination, a comparison may be made by using the weighted sum between the degree of polarization ρ**1** obtained from the first polarization image and the degree of polarization ρ**2** obtained from the second polarization image in step S**201** of FIG. **19**.

[0204] As shown in FIG. **27**, the light emitting section **101** including a plurality of light emitting devices **207** and **207-2**

may be used to emit polarized light of different polarization states from the light emitting devices **207** and **207-2**. In such a case, the plurality of light emitting devices **207** and **207-2** are preferably provided near each other. FIG. **27** is a diagram schematically showing the arrangement of the light emitting devices **207** and **207-2**, the image capture device **202**, the object, etc., when the area division of the present embodiment is performed. In FIG. **27**, like elements to those of FIG. **21** are denoted by like reference numerals to those of FIG. **21**, and will not be described in detail below.

[0205] FIG. **28** shows an exemplary configuration of a camera including therein the image processing apparatus of the present embodiment. In FIG. **28**, like elements to those of FIG. **3** are denoted by like reference numerals to those of FIG. **3**, and will not be described in detail below.

[0206] The illumination control section **102** shown in FIG. **28** changes the main axis direction of the polarized light by switching between the light emitting device **207** and the light emitting device **207-2**, as a device serving as the light source. Specifically, the polarization main axis direction of the polarizer **205** for the light emitting device **207** and the polarization main axis direction of a polarizer **205-2** for the light emitting device **207-2** are perpendicular to each other. Therefore, as opposed to the apparatus shown in FIG. **3**, there is no need for the rotation mechanism **206**, thus allowing for a reduction in the size of the camera.

[0207] Note that while the patterned polarizer **201** is a photonic crystal in the present embodiment, it may be a polarizer element of a film type or a wire-grid type, or be a polarizer element of any other suitable principle as long as it is a polarizer element. Alternatively, images may be captured while rotating a polarizing plate attached in front of the lens of the image capture device, without using a patterned polarizer, to thereby obtain luminance values for different polarization main axes over time. This method is disclosed in Japanese Laid-Open Patent Publication No. 11-211433, for example.

[0208] Note that the light emitting device **207** is preferably provided near the image capture device **202**. This is because by employing such an arrangement, the shaded area occurring on the object by being illuminated by the light emitting device **207** becomes smaller. Since shading is not taken into consideration by the area dividing method of the present embodiment, an area division becomes difficult when there is a shading. In a shaded area, light beams are complicated due to influence from multiple reflection, etc., thus losing the reliability of the polarization information. Therefore, in a shaded area, the area division precision deteriorates. For improving the precision of the area division, it is important to ensure that shading is unlikely to occur.

[0209] The area dividing section **106** may divide an image into four areas of the "light source-dependent polarized area", the "light source-dependent non-polarized area", the "light source-independent polarized area" and the "light source-independent non-polarized area", instead of dividing an image into the "specular reflection area" and the "diffuse reflection area". This process will now be described in detail.

[0210] FIG. **29** shows an image division criterion for the area dividing section **106** of the present embodiment. FIG. **30** is a flow chart showing the flow of a process performed by the area dividing section **106** of the present embodiment. In FIG. **30**, like steps to those of FIG. **17** are denoted by like reference numerals to those of FIG. **17** and will not be described in detail below.

[0211] First, in order to perform an area division of dividing an image into a non-polarized area and a polarized area by determining whether each pixel belongs to the non-polarized area or the polarized area, the area dividing section **106** compares the magnitude of the degree of polarization $\rho 1$ of the pixel with the threshold Thρ to determine whether the degree of polarization ρ is greater than or equal to the threshold Thρ or smaller than the threshold Thρ (step S**201**). If the degree of polarization $\rho 1$ of the pixel is greater than or equal to the threshold Thρ (Yes in step S**201**), it is determined that the pixel is included in the polarized area, and it is determined whether the first light source dependency LDϕ estimated by the light source dependency estimation section **105** is greater than or equal to the threshold Thϕ (step S**203**). If the first light source dependency LDϕ is greater than or equal to the threshold Thϕ (Yes in step S**203**), it is determined that the pixel is included in the light source-dependent polarized area (step S**208**), and the process is ended.

[0212] On the other hand, if the first light source dependency LDϕ is smaller than the threshold Thϕ (No in step S**203**), it is determined that the pixel is included in the light source-independent polarized area (step S**209**), and the process is ended.

[0213] Note that the degree of polarization $\rho 1$ of the pixel is smaller than the threshold Thρ (No in step S**201**), it is determined that the pixel is included in the non-polarized area, and a comparison is made as to whether the first light source dependency LDϕ estimated by the light source dependency estimation section **105** is greater than or equal to the threshold Th$\phi 2$ (step S**210**). If the first light source dependency LDϕ is greater than or equal to the threshold Th$\phi 2$ (Yes in step S**210**), it is determined that the pixel is included in the light source-dependent non-polarized area (step S**211**), and the process is ended. On the other hand, if the first light source dependency LDϕ is smaller than the threshold Th$\phi 2$ (No in step S**210**), it is determined that the pixel is included in the light source-independent non-polarized area (step S**212**), and the process is ended.

[0214] The threshold Th$\phi 2$ of the light source dependency in step S**210** may be set to be equal to the threshold Thϕ in step S**203**. The threshold Thρ of the degree of polarization and the threshold Thϕ of the first light source dependency LDϕ may be set as described above. Moreover, step S**203** and step S**210** may use different thresholds, instead of using the same threshold Thϕ. In such a case, since it is believed that the brightness resolution in the non-polarized area is smaller than that in the polarized area, the value Th$\phi 2$ is preferably set to be smaller than Thϕ.

[0215] Note that in order to solve the problem of a shaded area, "shaded area" may be added to areas into which the division is performed by the area dividing section **106**, as will be described later.

[0216] As described above, by using the area dividing method of the present invention, it is possible to perform an area division using the polarization information and the light source dependency. Such an area division is capable of a division between the specular reflection area and the diffuse reflection area taking into consideration the polarized component of the diffuse reflection component.

Second Embodiment

[0217] Next, the outline of an image processing apparatus according to a second embodiment of the present invention will be described. The image processing apparatus of the

present embodiment calculates the light source dependency by changing the position of the illumination section (light source position). An area division of the object is performed by utilizing the light source dependency resulting from the changes of the polarization information and the light source position.

[0218] FIG. **31** is a block diagram of an image processing apparatus of the present embodiment. In FIG. **31**, like elements to those of FIG. **1** are denoted by like reference numerals to those of FIG. **1**, and will not be described in detail below. A difference from the first embodiment is that an illumination position changing section **112** is provided, instead of the illumination control section **102**. With the image processing apparatus of the present embodiment, the position of the light emitting device **207** is changed by the illumination position changing section **112**, instead of changing the main axis direction of the polarized light by the illumination control section **102**.

[0219] The polarization phase resulting when the non-polarized light is emitted onto the object is dependent on the normal information of the object. However, the relationship changes depending on the specular reflection component and the diffuse reflection component.

[0220] First, consider the specular reflection component. The surface normal of the object has two degrees of freedom. It is herein determined by obtaining two angles: one being the incident plane that contains the incident light beam and the normal vector of the point of incidence (observation point), and the other being the angle of incidence within the incident plane. It is known that the incident plane of the specular reflection component is equal to the angle at which the brightness is at minimum in FIG. **6** obtained from the polarization image (for example, Ondfej Drbohlav and Sara Radim, "Using polarization to determine intrinsic surface properties", Proc. SPIE Vol. 3826, pp. 253-263, 1999).

[0221] Next, consider the diffuse reflection component. As described above, the surface normal of the object has two degrees of freedom. It is herein determined by obtaining two angles: one being the emittance plane that contains the light beam of exit light that is exiting from the object surface after repeated scattering and the normal vector of the emittance point (observation point), and the other being the emittance angle within the emittance plane. It is known that the emittance plane of the diffuse reflection component is equal to the angle at which the brightness is at maximum in FIG. **6** obtained from the polarization image (for example, U.S. Pat. No. 5,028,138). That is, while the polarization phase information is dependent on the angle of incidence in the specular reflection component, it is not dependent on the angle of incidence in the diffuse reflection component. If the light source position is changed while fixing the camera position, only the angle of incidence changes. Therefore, while the polarization characteristics vary in the specular reflection component, the polarization characteristics do not vary in the diffuse reflection component.

[0222] This is also related to the fact that since the specular reflection component occurs only in a partial area of the object that is near regular reflection, an area that has been a specular reflection area may become a diffuse reflection area as a result of changing the light source position. In any case, if the light source position is changed while fixing the camera position, the polarization characteristics vary in many specular reflection components, but the polarization characteristics do not vary in most of the diffuse reflection components. With the area dividing method of the present embodiment, an area division is performed utilizing this characteristic.

[0223] FIG. **32** is a flow chart showing the flow of a process of the area dividing method of the present embodiment. In FIG. **32**, like steps and corresponding steps to those of FIG. **2** are denoted by like reference numerals to those of FIG. **2** and will not be described in detail below. Moreover, FIG. **33** shows an exemplary configuration of a camera including therein the area dividing device of the present embodiment. In FIG. **33**, like elements and corresponding elements to those of FIG. **3** are denoted by like reference numerals to those of FIG. **3** and will not be described in detail below.

[0224] The illumination position changing section **112** (FIG. **31**) of the present embodiment is implemented by an illumination position changing device **213** shown in FIG. **33**, for example. The illumination position changing device **213** changes the position of the light emitting device **207**, and is implemented by using a motor, or the like. The light emitting device **207** may be attached to a moving portion of a robot, such as the arm. The image processing apparatus may include a plurality of light emitting devices **207** and **207-2**. FIG. **34** shows an exemplary configuration of a camera including therein an area dividing device of the present embodiment having a plurality of light emitting devices **207** and **207-2**. In such a case, the illumination position changing device **213** can vary the position of the light emitting device (light source position) by switching between the light emitting devices **207** and **207-2**.

[0225] In FIG. **32**, the illumination section **101** emits non-polarized light from the light emitting device **207** that is at the light source position specified by the control section **120** (step S**301**). The polarization image capturing section **103** receives light, by means of an image sensor, from the object through the patterned polarizer **201**, thus obtaining a third polarization image, which is an image including polarization information (step S**102**). This is achieved by the control section **120** synchronizing the illumination unit **121** and the polarization information obtaining section **122** with each other. Then, the patterned polarizer has three or more polarization main axis angles, as described above. The polarization information obtaining section **104** generates polarization information, which is information regarding the received polarized light, as described above (step S**103**). The illumination position changing section **112** moves the illumination section **101** so that the light emitting device **207** that is at a different position from that of step S**101** emits light, and the illumination section **101** emits non-polarized light onto the object from a position different from that of step S**301** (step S**302**).

[0226] The polarization image capturing section **103** again receives light, by means of an image sensor, from the object through the patterned polarizer **201**, thus obtaining a fourth polarization image (step S**105**). This is achieved by the control section **120** synchronizing the illumination unit **121** and the polarization information obtaining section **122** with each other. The third polarization image and the fourth polarization image are polarization images between which the light source (the light emitting device **207**) position of the illumination section **101** is changed. The polarization information obtaining section **104** again generates polarization information, which is information regarding the received polarized light, by using the correspondence with the brightness of the light having passed through the three-way or more polarizer, for each of unit pixels of the captured fourth polarization image (step S**106**). The light source dependency estimation section

105 estimates the light source dependency by making a comparison between the polarization information obtained by the polarization information obtaining section from the third polarization image and the fourth polarization image (step S**107**). The area dividing section **106** performs an area division by using the polarization information generated by the polarization information obtaining section **104** and the light source dependency information estimated by the light source dependency estimation section **105** (step S**108**).

[0227] This process will now be described in detail with reference to the drawings.

[0228] In step S**301**, the illumination section **101** emits non-polarized light from the light emitting device **207** that is at the light source position specified by the control section **120**. This may be done by forming the illumination section **101** from a plurality of light emitting devices **207**, and by switching between the light emitting devices **207** and **207-2** from which light is emitted by means of the illumination position changing section **112**, thereby changing the light source position. FIG. **35** is a system diagram showing the shooting conditions for the area division of the present embodiment. In FIG. **35**, like elements to those of FIG. **21** are denoted by like reference numerals to those of FIG. **21**, and will not be described in detail below.

[0229] The illumination position changing section **112** may vary the light source position by moving the light emitting device **207** by means of the illumination position changing device **213**. The illumination position changing device **213** may be implemented by a motor, or the like. The light emitting device **207** may be provided at a moving portion of a robot. FIG. **36** is a system diagram showing the shooting, conditions for the area division of the present embodiment. In FIG. **36**, like elements to those of FIG. **35** are denoted by like reference numerals to those of FIG. **35**, and will not be described in detail below.

[0230] In step S**102**, the polarization image capturing section **103** receives light, by means of an image sensor, from the object through the patterned polarizer **201**, as described above, thus obtaining a third polarization image, which is an image including polarization information. This is achieved by the control section **120** synchronizing the illumination unit **121** and the polarization information obtaining section **122** with each other.

[0231] In step S**103**, the polarization information obtaining section **104** generates polarization information, which is information regarding the received polarized light, by using the correspondence with the brightness of the light having passed through the three-way or more polarizer, for each of unit pixels of the captured third polarization image, as described above.

[0232] In step S**302**, the illumination position changing section **112** controls the illumination section **101** so that light is emitted from the light emitting device **207-2** that is at a position different from that of step S**301**, so that the illumination section **101** emits light onto the object from a position different from that of step S**301**. This can be achieved, as described above, by forming the illumination section **101** from a plurality of light emitting devices **207** and **207-2**, or by moving the light emitting device **207**, so as to vary the light source position.

[0233] In step S**105**, the polarization image capturing section **103** receives light, by means of an image sensor, from the object through the patterned polarizer **201**, as described above, thus again capturing a fourth polarization image, which is an image including polarization information. This is achieved by the control section **120** synchronizing the illumination unit **121** and the polarization information obtaining section **122** with each other. As compared with the third polarization image, the fourth polarization image is an image of the same object, but only with a different polarization state of the emitted light.

[0234] In step S**106**, as described above, the polarization information obtaining section **104** generates polarization information, which is information regarding the received polarized light, by using the correspondence with the brightness of the light having passed through the three-way or more polarizer, for each of unit pixels of the captured fourth polarization image, as described above.

[0235] In step S**107**, as described above, the light source dependency estimation section **105** estimates the light source dependency by making a comparison between the polarization information obtained by the polarization information obtaining section from the third polarization image and the fourth polarization image. Herein, the light source dependency is estimated by making a comparison between the polarization phase information, as polarization information.

[0236] In step S**108**, the area dividing section **106** performs an area division by using the polarization information generated by the polarization information obtaining section **104** and the light source dependency information estimated by the light source dependency estimation section **105**, as described above. The image division criterion of the area dividing section **106** is similar to FIG. **16**, and the flow chart showing the flow of the process performed by the area dividing section **106** is also similar to FIG. **17**.

[0237] FIGS. **37** to **42** show results of performing the area division of the present embodiment. FIG. **37** shows the polarization information obtained by the polarization information obtaining section **104** when the position of the light emitting device **207** is changed by the illumination position changing section **112** where the object is a globe. In this figure, FIG. **37**(*a*) shows the degree of polarization ρ**3** obtained from the third polarization image captured with the light emitting device **207** arranged toward the right side of the image, FIG. **37**(*b*) shows the polarization phase φmax**3** obtained from the third polarization image, FIG. **37**(*c*) shows the degree of polarization ρ**4** obtained from the fourth polarization image captured with the light emitting device **207-2** arranged toward the upper side of the camera, FIG. **37**(*d*) shows the polarization phase φmax**4** obtained from the fourth polarization image, and FIG. **37**(*e*) shows the first light source dependency LDφ obtained from the polarization phases φmax**3** and φmax**4**. Note that in FIG. **37**(*e*), white represents the value of the first light source dependency LDφ being 1, and black represents the value being 0. FIG. **38** shows the images of FIG. **37** in a schematic manner (with shading emphasized). In the figure, areas (A**41** to E**45**) correspond to the areas in FIG. **39**. FIG. **39** shows views obtained by dividing each image of FIG. **7** into a plurality of areas based on the high/low of the brightness.

[0238] FIG. **40** is a schematic diagram showing the positional relationship between the light emitting devices **207** and **207-2** and the image capture device **202** in this process. FIG. **41** shows results of performing the area division of the present embodiment by using the polarization information of FIG. **37**. In this figure, FIG. **41**(*a*) shows pixels of the third polarization image where the degree of polarization ρ**3** is greater than or equal to the threshold Thρ in step S**201**. FIGS. **41**(*b*),

(*c*) and (*d*) show the diffuse reflection non-polarized area, the specular reflection polarized area and the diffuse reflection polarized area, respectively, divided by the area division of the present embodiment. FIG. **41**(*e*) shows the diffuse reflection area, which is obtained as the union of the diffuse reflection non-polarized area and the diffuse reflection polarized area. In FIG. **41**, white pixels represent divided areas. With the conventional method of only using the degree of polarization, FIG. **41**(*a*) will be divided as a specular reflection area and FIG. **41**(*b*) as a diffuse reflection area, thereby causing a significant error near the occluding edge, as described above. On the other hand, with the area dividing method of the present embodiment, the light source dependency is used, in addition to the polarization information, and therefore FIG. **41**(*c*) is divided as a specular reflection area and FIG. **41**(*e*) as a diffuse reflection area. Thus, it is possible to perform an accurate area division as compared with the conventional method.

[0239] FIG. **42** shows results where the degree of polarization ρ**4** obtained from the fourth polarization image is used, instead of making a comparison using the degree of polarization ρ**3** obtained from the third polarization image, in step S**201**. In this figure, FIG. **42**(*a*) shows pixels of the fourth polarization image where the degree of polarization ρ**4** is greater than or equal to the threshold Thρ in step S**201**. FIGS. **42**(*b*), (*c*) and (*d*) show the diffuse reflection non-polarized area, the specular reflection polarized area and the diffuse reflection polarized area, respectively, divided by the area division of the present embodiment. FIG. **42**(*e*) shows the diffuse reflection area, which is obtained as the union of the diffuse reflection non-polarized area and the diffuse reflection polarized area. In FIG. **42**, white pixels represent divided areas. As with FIG. **41**, no matter which input image is used, the area dividing method of the present embodiment, which uses the light source dependency in addition to the polarization information, is capable of performing an accurate area division as compared with the conventional method. However, data are disturbed in the background area In FIGS. **41** and **42**. As described above, this is because the brightness resolution was low in the background area since it was very dark therein. Therefore, the reliability of the polarization information is decreased, and the data is disturbed. By increasing the brightness of the background area by elongating the exposure time, it is possible to obtain polarization information of a sufficient precision even in the background area. The background area may be masked so that it is excluded from the area dividing process. The area division has also failed for the shaded area. As described above, this is because the area dividing method of the present embodiment does not take shading into consideration.

[0240] The area dividing section **106** may perform an area division taking shaded areas into consideration. In such a case, it is preferred that the brightness information of the image is used, in addition to the polarization information and the light source dependency information. FIG. **43** shows an image division criterion for the area dividing section **106** in this process. FIG. **44** is a flow chart showing the flow of the process performed by the area dividing section **106** of the present embodiment which performs an area division including shaded areas. In FIG. **44**, like steps to those of FIG. **17** are denoted by like reference numerals to those of FIG. **17** and will not be described in detail below. This process will now be described in detail.

[0241] First, in order to estimate whether the pixel is a shaded area, the area dividing section **106** compares the set threshold and the luminance value with each other so as to determine whether the luminance value is less than or equal to the threshold (step S**401**). As described above, this utilizes the fact that the luminance value is low in a shaded area, and estimates, as a shaded area, a pixel whose luminance value is less than or equal to the threshold. Such a threshold for estimating the shaded area may be determined experimentally, and may be set to 256, for example, for a 16-bit monochrome image. The luminance value for detecting the shaded area may be the polarization maximum luminance value Imax or the polarization minimum luminance value Imin obtained by the polarization information obtaining section **104**, or the average value or the weighted average value (e.g., Imax+2·Imin) between the polarization maximum luminance value Imax and the polarization minimum luminance value Imin. Particularly, it is very effective to use the polarization minimum luminance value Imin, because the influence of the specular reflection component, where the possibility of overexposure is high and the luminance values will be very high, can be made small. Imax+Imin, which is the average value, is an image equivalent to an image captured under a non-polarized light source where no polarizer is provided. Therefore, by performing an image process by using the average value, it is possible to perform a process similar to normal, processes where polarized light is not used.

[0242] If the luminance value of the pixel is less than or equal to the threshold (Yes in step S**401**), it is determined that the pixel is a shaded area (step S**402**), and the process is ended. On the other hand, if the luminance value of the pixel is greater than or equal to the threshold (No in step S**401**), it is determined that the pixel is not a shaded area, and the process proceeds to step S**201** of FIG. **17**, thus performing an area dividing process described above.

[0243] The shaded area may be further divided into an attached shadow area and a cast shadow area by using the polarization information. This process will now be described in detail.

[0244] First, an attached shadow and a cast shadow will be described. FIG. **45** is a schematic diagram illustrating the classification of shading into an attached shadow and a cast shadow. Here, the object **604** placed on a plane **605** is illuminated by a light source **602**. In this figure, reference numerals **606** and **607** each denote a shading. The reference numeral **606** is an attached shadow produced because the normal of the object **604** is not facing toward the light source **602**. The reference numeral **607** is a cast shadow produced on **605** because the light is blocked by the object **604**, which is a light-blocking object.

[0245] Next, the difference in polarization characteristics between an attached shadow and a cast shadow will be described. First, it is assumed that images are captured in an image-capturing scene that satisfies Condition 3 below, which holds in almost any image-capturing scene on the ground.

[0246] Condition 3: "in an image-capturing scene where the object is present, there exists an object having a large surface near the object, with a light source present in the opposite direction from the large surface with respect to the object"

[0247] This holds in such an image-capturing scene as follows, for example.

[0248] 1. In an indoor scene, a ball, being the object, is placed on a desk. The ball is illuminated by a fluorescent light installed on the ceiling.

[0249] 2. In an indoor scene, a person, being the object, is sitting on a chair placed on the floor surface. The person is illuminated by sunlight coming in through a window.

[0250] 3. In an outdoor scene, an automobile, being the object, is running on a road. The object is illuminated by sunlight.

[0251] Since a wall or a building also has a large surface, this condition holds in almost any image-capturing scene on the ground.

[0252] First, consider an attached shadow, for cases where Condition 3 holds. As shown in FIG. **45**, an attached shadow is a shading produced because the normal of the object is facing in the opposite direction to the light source. Herein, it is believed from Condition 3 that multiple reflection light is incident on the attached shadow from various directions, in view of the fact that there is a large surface in the opposite direction to the light source and the fact that there are actually many rays of diffracted light (multiple reflection light) in the shaded area. That is, it is believed that there exists multiple reflection light, which is to be regular reflection, for the camera and the normal of the pixel having an attached shadow. FIG. **46** is a schematic diagram showing this. This figure shows the image capture device **601** including therein the area dividing device of the present embodiment.

[0253] It is known that the reflection characteristic of an object surface is represented as the sum of the specular reflection component, which is a gloss, and the diffuse reflection component, which is a mat reflection component, as described above. While the diffuse reflection component is observed irrespective of the direction of the light source illuminating the object, the specular reflection component is a component that is strongly dependent on direction and is observed only when the light source is present generally in the regular reflection direction with respect to the normal direction and the viewing direction of the object. This holds also for the polarization characteristic.

[0254] It is known that where the object is an object that causes specular reflection, which is a gloss, if light is coming from every direction, the object is strongly influenced by the specular reflection, which is a regular reflection component (for a transparent object, see, for example, Megumi Saito, Yoichi Sato, Katsushi Ikeuchi, Hiroshi Kashiwagi, "Measurement of Surface Orientations of Transparent Objects Using Polarization in Highlight", Trans. of IEICE, D-II, Vol. J82-D-II, No. 9, pp. 1383-1390, 1999). Thus, an attached shadow has a polarization characteristic of specular reflection.

[0255] From FIGS. **72** and **73** above, showing the degrees of polarization of the specular reflection component and the diffuse reflection component, it can be seen that if light is coming from every direction, the degree of polarization of the specular reflection component is higher than that of the diffuse reflection component. From this, it is speculated that the specular reflection component will be dominant also for the polarization characteristic.

[0256] Excluding an occluding edge, and the like, where the emittance angle is close to 90°, the degree of polarization of the specular reflection component is higher than that of the diffuse reflection component, as can be seen from FIGS. **72** and **73**. Therefore, an attached shadow, which exhibits the reflection characteristic of the specular reflection component, has a relatively high degree of polarization.

[0257] Next, consider a cast shadow. As shown in FIG. **45**, a cast shadow is a shading produced as light is blocked by some light-blocking object. In view of Condition 3, a cast shadow is likely to occur on a surface that has a normal direction close to that of the large surface. Therefore, multiple reflection light is incident only from limited directions, as compared with an attached shadow. From this, it is believed that it is unlikely that a light source exists in the regular reflection direction. FIG. **47** is a schematic diagram showing this.

[0258] Moreover, as shown in FIG. **73**, the degree of polarization of the diffuse reflection component is relatively low. From this, it can be seen that a cast shadow has a relatively small polarization component. In a shaded area, the brightness itself is small, and it is therefore very difficult to estimate the small polarization component. Thus, a cast shadow has a very large polarization estimation error.

[0259] In summary, the polarization characteristics of shaded areas are classified as follows.

[0260] Attached shadow

[0261] High degree of polarization, low polarization estimation error.

[0262] Exhibits specular reflection characteristic in many cases.

[0263] Cast shadow

[0264] Low degree of polarization, large polarization estimation error.

[0265] Exhibits diffuse reflection characteristic in many cases.

[0266] By using this classification criterion, shadings are divided into the attached shadow and the cast shadow.

[0267] FIG. **48** shows an image division criterion for the area dividing section **106** in this process. FIG. **49** is a flow chart showing the flow of the process performed by the area dividing section **106** of the present embodiment which performs an area division including the attached shadow and the cast shadow. In FIG. **49**, like steps to those of FIG. **44** are denoted by like reference numerals to those of FIG. **44** and will not be described in detail below. This process will now be described in detail.

[0268] First, in order to estimate whether the pixel is a shaded area, the area dividing section **106** compares the set threshold and the luminance value with each other so as to determine whether the luminance value is less than or equal to the threshold (step S**401**). As described above, this utilizes the fact that the luminance value is low in a shaded area, and estimates, as a shaded area, a pixel whose luminance value is less than or equal to the threshold. If the luminance value of the pixel is greater than the threshold, it is determined that the pixel is not a shaded area (No in step S**401**), and the process proceeds to step S**201** of FIG. **17**, thus performing an area dividing process described above. On the other hand, if the luminance value of the pixel is less than or equal to the threshold, it is determined that the pixel is a shaded area (Yes in step S**401**), and it is determined whether the polarization estimation error E obtained by the polarization information obtaining section **104** is greater than the threshold Th_Err (step S**403**). If the polarization estimation error E is less than or equal to the threshold Th_Err (No in step S**403**), it is determined that the pixel is an attached shadow (step S**404**), and the process is ended. On the other hand, if the polarization estimation error E is greater than the threshold Th_Err (Yes in

step S403), it is determined that the pixel is a cast shadow (step S405), and the process is ended.

[0269] The threshold Th_Err for this process may be determined with reference to the luminance value of the captured image, the amplitude component A of Expression 1, or the bias component C. For example, the threshold Th_Err may be determined as follows when it is determined with reference to the amplitude component A.

[Exp. 14]

$$Th_Err=(Th_E)^2\cdot(2A)^2\cdot N \qquad \text{Expression 14}$$

[0270] This expression indicates how much the polarization estimation error E differs from the amplitude component A. Herein, Th_E is an arbitrary positive constant, which may be determined experimentally, and may be set to 0.3, for example. N is the number of samples described above.

[0271] The criterion for dividing shadings into the attached shadow and the cast shadow is not limited to polarization estimation error information, but may also be degree-of-polarization information, for example. This process will now be described in detail.

[0272] FIG. **50** shows an image division criterion for the area dividing section **106** in this process. FIG. **51** is a flow chart showing the flow of the process performed by the area dividing section **106** of the present embodiment which performs an area division including shaded areas. In FIG. **51**, like steps to those of FIG. **49** are denoted by like reference numerals to those of FIG. **49** and will not be described in detail below. This process will now be described in detail.

[0273] In order to estimate whether the pixel is a shaded area, as described above, the area dividing section **106** compares the set threshold and the luminance value with each other so as to determine whether the luminance value is less than or equal to the threshold (step S401). If the brightness is above the threshold (No in step S401), the process proceeds to step S201 of FIG. **17**, thus performing an area dividing process described above. On the other hand, if the brightness is less than or equal to the threshold (Yes in step S401), it is determined that the pixel is a shaded area, and it is determined whether the degree of polarization ρ obtained by the polarization information obtaining section **104** is greater than the threshold Thρ**3** (step S406). If the degree of polarization ρ is greater than or equal to the threshold Thρ**3** (No in step S406), it is determined that the pixel is an attached shadow (step S404), and the process is ended. On the other hand, if the polarization estimation error E is smaller than the threshold Thρ**3** (Yes in step S406), it is determined that the pixel is a cast shadow (step S405), and the process is ended.

[0274] In this process, the threshold Thρ**3** of the degree of polarization in step S406 may be set to be equal to the threshold Thρ of step S203. Step S203 and step S406 may use different thresholds, instead of using the same threshold Thρ. In such a case, since it can be assumed that the brightness resolution in a shaded area is smaller than the polarized component, the value of Thρ**3** is preferably set to be smaller than Thρ.

[0275] As described above, by using the area dividing method of the present invention, it is possible to perform an area division using the polarization information and the light source dependency. Such an area division is capable of a division between the specular reflection component and the diffuse reflection component taking into consideration the polarized light of the diffuse reflection component. It is also possible to perform an area division using the brightness information, in addition to the polarization information and the light source dependency. Such an area division is capable of a division between the specular reflection area and the diffuse reflection area taking into consideration of a shaded area, and even a division between the attached shadow and the cast shadow.

Third Embodiment

[0276] FIG. **52** shows a block diagram of an area dividing system of the present embodiment. In FIG. **52**, like elements to those of FIG. **1** are denoted by like reference numerals to those of FIG. **1**, and will not be described in detail below.

[0277] A difference from the first embodiment is that an illumination device **108** and an area dividing device **109** are separated from each other, and the area dividing device **109** includes a captured image determination section **107**. FIG. **53** is a flow chart showing the flow of a process of an area dividing method of the present embodiment. In FIG. **53**, like steps to those of FIG. **2** are denoted by like reference numerals to those of FIG. **2** and will not be described in detail below. Moreover, FIG. **54** shows an exemplary configuration of a camera including therein the area dividing device of the present embodiment, and an illumination device. In FIG. **54**, like elements to those of FIG. **3** are denoted by like reference numerals to those of FIG. **3**, and will not be described in detail below.

[0278] The area dividing system of the present embodiment is an area dividing system, including the illumination device **108** and the area dividing device **109**, for capturing an image of an object and thereby performing an optical area division of the surface of the object, wherein the illumination device **108** includes the illumination section **101** for emitting linearly-polarized light onto the object, and the illumination control section **102** for changing the polarization state of the linearly-polarized light of the illumination section **101**, thereby emitting polarized light of different main axis directions onto the object over time. The area dividing device **109** includes: the polarization image capturing section **103** for receiving light having passed through a three-way or more polarizer having different polarization main axis angles to thereby obtain polarization image of the object; the captured image determination section **107** for comparing a polarization image captured in the past by the polarization image capturing section **103** with a currently-captured polarization image to thereby determine whether the captured polarization states have changed sufficiently; the polarization information obtaining section **104** for generating, from the obtained polarization image, polarization information, which is information regarding the received polarized light, by using the correspondence with the brightness of the light having passed through the three-way or more polarizer, for each of unit pixels of the polarization image; the light source dependency estimation section **105** for estimating light source dependency information by making a comparison between the polarization information generated by the polarization information obtaining section **104** as the polarization state of the illumination section **101** is changed by the illumination control section **102**; and the area dividing section **106** for performing an area division by using the polarization information generated by the polarization information obtaining section **104** and the light source variation information estimated by the light source dependency estimation section **105**.

[0279] Next, the area dividing device **109** of the present embodiment will be described in detail.

[0280] First, in step S**102**, the polarization image capturing section **103** receives light, by means of an image sensor, from the object through the patterned polarizer **201**, as described above, thus obtaining a first polarization image, which is an image including polarization information.

[0281] In step S**103**, the polarization information obtaining section **104** generates the polarization information, which is information regarding the received polarized light, by using the correspondence with the brightness of the light having passed through the three-way or more polarizer, for each of unit pixels of the captured first polarization image, as described above.

[0282] In step S**105**, the polarization image capturing section **103** receives light, by means of an image sensor, from the object through the patterned polarizer **201**, as described above, thus again capturing a second polarization image, which is an image including polarization information.

[0283] In step S**501**, the captured image determination section **107** makes a comparison between the first polarization image and the second polarization image to determine whether the captured polarization states have changed sufficiently. This can be done by making a comparison between the luminance values of the captured polarization images. Specifically, a difference image between the captured second polarization image and the captured first polarization image may be produced, and it may be determined that the captured polarization states have changed sufficiently if the maximum value of the difference value is greater than or equal to a threshold. The threshold for this process may be determined experimentally, and may be set to 1000, for example, for a 16-bit monochrome image.

[0284] With the area dividing method of the present embodiment, the illumination device **108** and the area dividing device **109** are provided separately, and the illumination device **108** is not synchronized with the area dividing device **109**. Therefore, the area dividing device **109** determines whether the polarization states of the captured images have changed by means of the area determination section **107**.

[0285] If the captured image determination section **107** determines that the polarization states have changed sufficiently (Yes in step S**501**), in step S**106**, the polarization information obtaining section **104** generates polarization information, which is information regarding the received polarized light, by using the correspondence with the brightness of the light having passed through the three-way or more polarizer, for each of unit pixels of the captured second polarization image, as described above. On the other hand, if the captured image determination section **107** determines that the polarization states have not changed sufficiently (No in step S**501**), the area dividing device **109** again obtains a second polarization image, which is an image including polarization information, as described above. The process after step S**106** is similar to that of the first embodiment, and will not be further described below.

[0286] Polarization information may be obtained, instead polarization images, in order to determine whether the captured polarization states have changed sufficiently. In such a case, the difference between second polarization information and first polarization information may be produced, and it may be determined that the captured polarization states have changed sufficiently if the maximum value of the difference is greater than or equal to a threshold. The threshold for this process may be determined experimentally, and the threshold may be set to 90 degrees where the difference in polarization phase is calculated as the polarization information, and to 0.1 where the difference in the degree of polarization is calculated as the polarization information.

[0287] FIG. **55** is a flow chart showing the flow of the process of an area dividing method of the present embodiment. In FIG. **55**, like steps to those of FIG. **53** are denoted by like reference numerals to those of FIG. **53** and will not be described in detail below.

[0288] With the area dividing system of the present embodiment, it is possible to realize the area dividing device **109** of an even smaller size by separating the illumination device **108** and the area dividing device **109** from each other.

[0289] The illumination device **108** and the area dividing device **109** may be synchronized with each other, wherein the area dividing device **109** captures images based on the synchronization signals from the illumination device **108**. This process will be described.

[0290] FIG. **56** shows a block diagram of an image processing system of the present embodiment. In FIG. **56**, like elements to those of FIG. **52** are denoted by like reference numerals to those of FIG. **52**, and will not be described in detail below. A difference from the configuration shown in FIG. **52** is that the illumination device **108** and the area dividing device **109** both include communication sections **110** and **111**, and the captured image determination section **107** is absent in the area dividing device **109**. FIG. **57** is a flow chart showing the flow of a process of the area dividing method of the present embodiment. In FIG. **57**, like steps to those of FIG. **2** are denoted by like reference numerals to those of FIG. **2** and will not be described in detail below. Moreover, FIG. **58** shows an exemplary configuration of a camera including therein the area dividing device of the present embodiment, and an illumination device. In FIG. **58**, like elements to those of FIG. **54** are denoted by like reference numerals to those of FIG. **54**, and will not be described in detail below.

[0291] As described above, the illumination section **101** emits polarized light which is polarized in a main axis direction specified by the illumination control section **102**, in step S**101**. Then, the illumination device **108** transmits, by means of a communication device **209**, a signal indicating a light emission to the area dividing device **109** (step S**502**). When the area dividing device **109** receives the signal indicating a light emission at a communication device **210** (step S**503**), the polarization image capturing section **103** receives light, by means of an image sensor, from the object through the patterned polarizer **201**, as described above, thus obtaining a first polarization image, which is an image including polarization information (step S**102**). Then, the patterned polarizer has three or more polarization main axis angles, as described above. The polarization information obtaining section **104** generates polarization information, which is information regarding the received polarized light as described above (step S**103**), and the area dividing device **109** transmits, by means of the communication device **210**, a signal indicating the completion of image-capturing of the first polarization image to the illumination device **108** (step S**504**). As the illumination device **108** receives the signal indicating the completion of image-capturing at the communication device **209** (step S**505**), the illumination control section **102** controls the illumination section **101** so that polarized light in a polarization state that is different from that when obtaining the first polarization image is emitted onto the object, as described above. Then, the illumination section **101** again emits polar-

ized light which is polarized in a main axis direction specified by the illumination control section **102** onto the object (step S**104**). Thereafter, the illumination device **108** again transmits, by means of the communication device **209**, a signal indicating a light emission to the area dividing device **109** (step S**506**). As the area dividing device **109** receives the signal indicating a light emission at the communication device **210** (step S**507**), the area dividing device **109** obtains the second polarization image through steps S**105**-S**108** as described above, and finally performs an area division.

[0292] The illumination device **108** may include the illumination position changing section **112**, instead of the illumination control section **102**, and the position of the light source may be changed as described above. In the area dividing system of the present embodiment, the illumination device **108** and the area dividing device **109** are separated from each other, and the light emission and the image-capturing are synchronized with each other by communications, thus realizing an efficient area division with the area dividing device **109** of an even smaller size.

(Model-Based Image Synthesis Using Area Division)

[0293] The area division of the present invention is particularly effective for a model-based image synthesis process used in digital archives, etc. The model-based image synthesis is important as a method for interactively presenting captured image data since it is possible to arbitrarily vary the light source direction or the viewing direction of the captured image. It is very effective also for giving realism. Therefore, the model-based image synthesis process can be used in applications such as virtual museums or AR (Augmented Reality). Originally, such a model-based image synthesis divides a captured image into the specular reflection component and the diffuse reflection component, and uses a different model for each component. However, as described above, the separation between the specular reflection component and the diffuse reflection component is insufficient, and the image quality therefore deteriorates. The cause of this problem is as follows. Since the parameter estimation in each model uses the specular reflection component and the diffuse reflection component, which are different from actual components, the process will estimate parameters that are different from actual parameters. If an image is synthesized by using parameters different from the actual parameters, there will be a significant error in the output image when a viewpoint-converted image or a light source-varied image is generated, as described above.

[0294] By using the area dividing method of the present invention, it is possible to realize a model-based image synthesis with little image deterioration. This method will be described.

[0295] First, the concept of this process will be described. The image synthesis process of the present invention includes a parameter estimation device **300**, and an image synthesis apparatus **301**. The following five input information are used.

[0296] Diffuse reflection image of object

[0297] Specular reflection image of object

[0298] 3-dimensional shape information of object

[0299] Light source position/color/illuminance

[0300] Viewpoint/light source information in synthesized image

(Embodiment of Parameter Estimation Device and Image Synthesis Apparatus)

[0301] FIG. **59** is a block diagram showing a configuration of the parameter estimation device **300** and the image synthesis apparatus **301** according to one embodiment of the present invention.

[0302] The parameter estimation device **300** of FIG. **59** includes: an image capturing section **302** for capturing an image by using an image capture device; an area dividing section **303** for dividing an image into a specular reflection area and a diffuse reflection area by the area dividing method described above; a light source information estimating section **304** for estimating light source information, such as the direction, the position, the brightness, the color or the spectrum information, of the light source illuminating the object; a shape information obtaining section **305** for obtaining, as shape information, the normal information of the surface of the object or the 3-dimensional position information thereof; a parameter estimation section **306** for estimating a reflection model parameter by modeling the light source information estimated by the light source information estimating section for each area divided by the area dividing section **303** and the shape information obtained by the shape information obtaining section, from the captured image of the object; and a parameter DB (database) **307** for storing the reflection parameter estimated by the parameter estimation section **306**.

[0303] Moreover, the image synthesis apparatus **301** includes a viewpoint/light source information obtaining section **308** for obtaining the viewpoint or light source information of the image to be synthesized, and a rendering section **309** for synthesizing an image according to the viewpoint or light source information obtained by the viewpoint/light source information obtaining section **308** by using the model parameter information stored in the parameter DB **307**.

[0304] First, referring to FIGS. **60** and **61**, the flow of the process of the parameter estimation method of the present embodiment will be described. FIGS. **60** and **61** are flow charts showing the flows of the processes of the parameter estimation method and the image synthesis method according to the image synthesis method of the present embodiment.

[0305] In step S**601** of FIG. **60**, the image capturing section **302** captures an image of the object by the polarization image capturing section **103** and the polarization information obtaining section **104** described above to thereby obtain the weighted average value $Imax+2\cdot Imin$ between the polarization maximum luminance value Imax and the polarization minimum luminance value Imin. In step S**602**, the area dividing section **303** divides the image captured by the image capturing section **302** into a diffuse reflection area and a specular reflection area by the area dividing method described above.

[0306] In step S**603**, the light source information estimating section **304** obtains, as the light source information, the direction of the light source, as well as the color information and the illuminance information thereof. In step S**604**, the shape information obtaining section **305** obtains the surface normal information or the 3-dimensional position information of the object, which is the shape information of the object.

[0307] In step S**605**, the parameter estimation section **306** estimates the reflection parameter of each of the diffuse reflection image and the specular reflection image, which have been divided by the area dividing section **303**, by using the light source information estimated by the light source information estimating section and the shape information obtained by the shape information obtaining section. In step S**606**, the parameter DB **307** stores, as model parameters, the reflection parameter for the diffuse reflection component and the reflection parameter for the specular reflection component

obtained by the parameter estimation section **306**, and the shape information obtained by the shape information obtaining section **305**.

[0308] Next, referring to FIG. **61**, the flow of the process of the image synthesis estimation method will be described.

[0309] First, in step S**607**, the rendering section **309** calls the model parameter information stored in the parameter DB **307**. In step S**608**, the viewpoint/light source information obtaining section **308** obtains the viewpoint or the light source direction of the image to be synthesized, and also the color information or the illuminance information thereof. In step S**609**, the rendering section **309** synthesizes an image according to the viewpoint and the light source information obtained by the viewpoint/light source information obtaining section **308** by using the model parameter information stored in the parameter DB **307**.

[0310] FIG. **62** shows an exemplary configuration of a camera including therein an image synthesis apparatus of the present embodiment.

[0311] It is assumed that the area dividing section **303**, the light source information estimating section **304**, the shape information obtaining section **305**, the parameter estimation section **306** and the rendering section **309** shown in FIG. **59** are implemented by the CPU **204** of FIG. **61** executing a program. Note however that some or all of these functions may be implemented by hardware.

[0312] The viewpoint/light source information obtaining section **308** of FIG. **59** is carried out by an user interface section **212** of FIG. **61**. The memory **203** stores, as model parameters, the polarization image captured by the image capturing section **302**, the specular reflection component and the diffuse reflection component image obtained by the area dividing section **303**, the light source information estimated by the light source information estimating section, the shape information obtained by the shape information obtaining section **305**, the reflection parameter information estimated by the parameter estimation section **306**, and the viewpoint/light source information obtained by viewpoint/light source information obtaining section.

[0313] Each of the processes will now be described.

[0314] First, the parameter estimation device **300** of FIG. **59** will be described.

[0315] The image capturing section **302** captures an image of the object by using an image capture device such as a CCD or a CMOS. It is preferred that an image thus captured is recorded with a sufficient brightness resolution so that the specular reflection component where the brightness is very high and the diffuse reflection component are not saturated at the same time. Therefore, it is preferred to use an image capture device capable of shooting with a wide dynamic range, such as a cooled CCD camera or multiple exposure shooting. Such an image capturing section may use the weighted average value Imax+2·Imin between the polarization maximum luminance value Imax and the polarization minimum luminance value Imin obtained by the polarization information obtaining section **104** described above. Particularly, Imax+2·Imin, which is a weighted average value, is an image equivalent to an image captured under a linearly-polarized light source where no polarizer is provided. Therefore, by performing an image process by using the weighted average value, it is possible to perform a process similar to normal processes where polarized light is not used.

[0316] The area dividing section **303** of FIG. **59** divides an image captured by the image capturing section **302** into a diffuse reflection area and a specular reflection area by the area dividing method described above.

[0317] The light source information estimating section **304** obtains, as the light source information, the direction of the light source, as well as the color information and the illuminance information thereof. For example, a mirror surface of a known shape for estimating the light source information may be provided near the object, and it may be estimated from the image of the mirror surface captured by the image capturing section **302** (for example, Masayuki Kanbara and Naokazu Yokoya, "Geometric and Photometric Registration for Vision-based Augmented Reality", IEICE Technical Report, PRMU2002-190, pp. 7-12, 2003). This process will now be described in detail.

[0318] The process of the light source information estimating section **304** is performed by using a sphere **401**, which can be regarded as a mirror surface shown in FIG. **63**. The mirrored ball **401** is provided near the object, with a known position and a known normal direction. The image capturing section **302** captures an image of the mirrored ball **401**. The image-capturing environment is reflected as a glare on the mirrored ball **401**. The position of the glare reflection is such a position that the viewing direction and the direction toward the object being reflected are in a regular reflection relationship with respect to the normal direction on the mirrored ball. Therefore, if the position of the mirrored ball and the normal direction thereof are known, the direction of the object being reflected can be detected from the image of the reflection on the mirror surface. Taking into consideration the fact that the light source has a high luminance value, it is possible to obtain the direction of the light source by detecting high-brightness pixels from the captured image of the mirrored ball. Moreover, if the reflectance of the mirror surface is known, it is also possible to obtain light source illuminance information such as the color information or luminance of the light source.

[0319] The light source position information may be obtained, as the light source information, in addition to or instead of the direction of the light source. This may be done by using stereo image process techniques known in the field of image processing, wherein two such mirrored balls as described above are used, or a plurality of images captured while changing the position of the image capture device are used, for example.

[0320] Instead of always capturing the image of such a mirrored ball, light source information obtained through image-capturing previously may be used. This is advantageous in cases where the light source environment does not change, as with an indoor surveillance camera. In such a case, an image of a mirrored ball may be captured upon installment of the camera, to obtain the light source information.

[0321] The light source information estimating section **304** may estimate the light source direction by using the object, instead of using a reference object such as the sphere **401** which can be regarded as a mirror surface. This method will be described. First, in an area where an image of the object is captured, a pixel with the highest luminance value is selected. As will be described later, the normal direction of the pixel with the highest luminance value is known since the shape information obtaining section **305** has estimated the surface normal information, which is the shape information of the object. Assuming that the light source in the regular reflection direction is reflected as a glare in the pixel with the highest luminance value, the direction of the light source can be

obtained from the normal direction, as with the method using a reference object described above.

[0322] By providing the image capture device **601** with an illuminometer **211**, the incident illuminance may be measured as light source information. The method for using the incident illuminance information will be described later.

[0323] The shape information obtaining section **305** obtains the surface normal information or the 3-dimensional position information of the object, which is the shape information of the object. Means for obtaining the shape information of the object may be any existing method such as, for example, a slit-ray projection method, a patterned light projection method, or a laser radar method.

[0324] The obtainment of the shape information is not limited to these methods. For example, it may use a stereo vision using a plurality of cameras, a motion stereo method using the movement of the camera, a photometric stereo method using an image captured while changing the position of the light source, a method for measuring the distance from the object by using millimeter waves or ultrasonic waves, and also a method using polarization characteristics of the reflected light (e.g., U.S. Pat. No. 5,028,138 or Daisuke Miyazaki, Katsushi Ikeuchi, "A Method to Estimate Surface Shape of Transparent Objects by Using Polarization Raytracing Method", Trans. of IEICE, vol. J88-D-II, No. 8, pp. 1432-1439, 2005). Herein; a photometric stereo method and a method using polarization characteristics will be described.

[0325] The photometric stereo method is a method for estimating the normal direction and the reflectance of the object by using three or more images of different light source directions. For example, "H. Hayakawa, "Photometric Stereo under a light source with arbitrary motion", Journal of the Optical Society of America A, vol. 11, pp. 3079-89, 1994" is a method in which six or more points of an equal reflectance on the image are obtained as known information and used as a constraint so as to estimate the following parameters even with the light source position information being unknown.

[0326] Object information: normal direction and reflectance of each point on image

[0327] Light source information: light source direction and illuminance at point from which object is observed

[0328] Herein, a photometric stereo method is carried out, which uses only the diffuse reflection image, which is separated by the diffuse reflection/specular reflection separation method described above. This method results in a significant error for an object where there is specular reflection because the method originally assumes that the object reflects light totally in diffuse reflection. However, by using only the diffuse reflection area separated, it is possible to eliminate the estimation error due to the presence of the specular reflection component.

[0329] Diffuse reflection images of different light source directions are represented as a brightness matrix I_d as follows.

Expression 15

$$I_d = \begin{bmatrix} i_{d1(1)} & \Lambda & i_{dF(1)} \\ M & O & M \\ i_{d1(P)} & \Lambda & i_{dF(P)} \end{bmatrix} \quad \text{[Exp. 15]}$$

[0330] Herein, $i_{df(p)}$ represents the luminance value of the diffuse reflection image of the light source direction f at a pixel p. The number of pixels of the image is P, and the number of images captured with different light source directions is F. Now, by the Lambertian model, the luminance value of the diffuse reflection image can be expressed as follows.

[Exp. 16]

$$i_{f(p)} = (\rho_{dp} \cdot n_p^T) \cdot (t_f L_f) \quad \text{Expression 16}$$

[0331] Herein, ρ_{dp} is the reflectance (albedo) of the pixel p, n_p is the normal direction vector of the pixel p, t_f is the incident illuminance of the light source f, and L_f is the direction vector of the light source f.

[0332] Expression 15 and Expression 16 together yield the following expression.

[Exp. 17]

$$I = R \cdot N \cdot L \cdot T = S \cdot M \quad \text{Expression 17}$$

[0333] where

Expression 18

$$R = \begin{bmatrix} \rho_1 & & 0 \\ & O & \\ 0 & & \rho_P \end{bmatrix} \quad \text{[Exp. 18]}$$

$$N = [n_1 \ \Lambda \ n_P]^T = \begin{bmatrix} n_{1x} & n_{1y} & n_{1z} \\ M & M & M \\ n_{Px} & n_{Py} & n_{Pz} \end{bmatrix} \quad \text{[Exp. 19]}$$

$$L = [L_1 \ \Lambda \ L_F] = \begin{bmatrix} l_{x1} & \Lambda & l_{xF} \\ l_{y1} & \Lambda & l_{yF} \\ l_{z1} & \Lambda & l_{zF} \end{bmatrix} \quad \text{[Exp. 20]}$$

$$T = \begin{bmatrix} t_1 & & 0 \\ & O & \\ 0 & & t_F \end{bmatrix} \quad \text{[Exp. 21]}$$

$$S = [s_1 \ \Lambda \ s_P]^T = \begin{bmatrix} s_{1x} & s_{1y} & s_{1z} \\ M & M & M \\ S_{Px} & S_{Py} & S_{Pz} \end{bmatrix} = R \cdot N \quad \text{[Exp. 22]}$$

$$M = [M_1 \ \Lambda \ M_F] = \begin{bmatrix} m_{x1} & \Lambda & m_{xF} \\ m_{y1} & \Lambda & m_{yF} \\ m_{z1} & \Lambda & m_{zF} \end{bmatrix} = L \cdot T \quad \text{[Exp. 23]}$$

[0334] Herein, R is called the surface reflection matrix, N the surface normal matrix, L the light source direction matrix, T the light source intensity matrix, S the surface matrix, and M the light source matrix.

[0335] Using a singular value decomposition, Expression 17 can be developed as follows.

Expression 19

$$I = U \cdot \Sigma \cdot V \quad \text{[Exp. 24]}$$

-continued

$$U = [\,U' \quad U''\,] \qquad \text{[Exp. 25]}$$

$$\Sigma = \begin{bmatrix} \Sigma' & 0 \\ 0 & \Sigma'' \end{bmatrix}$$

$$V = \begin{bmatrix} V' \\ V'' \end{bmatrix}$$

$$U^T \cdot U = V^T \cdot V = V \cdot V^T = E \qquad \text{[Exp. 26]}$$

[0336] E is the unit matrix. U' is a P×3 matrix, U" is a P×(F−3) matrix, Σ' is a 3×3 matrix, Σ" is an (F−3)×(F−3) matrix, V' is a 3×F matrix, and V" is an (F−3)×F matrix. It can be assumed that U" and V" are orthogonal bases of signal components U' and V', respectively, i.e., noise components. By using the singular value decomposition, Expression 19 can be rearranged as follows.

[Exp. 27]

$$\hat{I}=U'\cdot\Sigma'\cdot V'=\hat{S}\cdot\hat{M} \qquad \text{Expression 20}$$

[Exp. 28]

$$\hat{S}=U'\cdot(\pm[\Sigma']^{1/2})$$

$$\hat{M}=(\pm[\Sigma']^{1/2})\cdot V'$$

[0337] That is, although the shape information and the light source information can be obtained simultaneously by solving Expression 20, the variability of the 3×3 matrix A below remains.

[Exp. 29]

$$S=\hat{S}\cdot A \qquad \text{Expression 21}$$

[Exp. 30]

$$M=A^{-1}\cdot\hat{M} \qquad \text{Expression 22}$$

[0338] Herein, A is any 3×3 matrix. It is necessary to obtain the matrix A in order to obtain the shape information and the light source information. This is satisfied, for example, if it is known that the reflectance is equal among six or more points on the image. For example, assuming that the reflectance is equal among arbitrary six points k**1** to k**6**,

[Exp. 31]

$$(s_{k1})^2=(s_{k2})^2=(s_{k3})^2=(s_{k4})^2=(s_{k5})^2=(s_{k6})^2=1 \qquad \text{Expression 23}$$

[0339] Expression 18, Expression 21 and Expression 23 together yield the following.

[Exp. 32]

$$(s_{ki})^2=(\hat{s}_{ki}{}^T\cdot A)^2=(\hat{s}_{ki}{}^T\cdot A)^T\cdot(\hat{s}_{ki}{}^T\cdot A)=(\hat{s}_{ki}{}^T\cdot A)\cdot(\hat{s}_{ki}{}^T\cdot A)^T=\hat{s}_{ki}{}^T\cdot A\cdot A^T\cdot\hat{s}_{ki}=1 \qquad \text{Expression 24}$$

[0340] Moreover, assuming that

[Exp. 33]

$$B=A\cdot A^T \qquad \text{Expression 25}$$

[0341] Expression 24 is as follows.

[Exp. 34]

$$\hat{s}_{ki}{}^T\cdot B\cdot\hat{s}_{ki}=1 \qquad \text{Expression 26}$$

[0342] Herein, from Expression 25, the matrix B is a symmetric matrix, and therefore the number of unknowns of the matrix B is 6. That is, Expression 26 can be solved if it is known that the reflectance is equal among six or more points on the image.

[0343] Once the matrix B is known, the matrix A can be solved by applying a singular value decomposition to Expression 25. Moreover, the shape information and the light source information are obtained from Expression 21 and Expression 22.

[0344] From the above, for an object of which six or more pixels sharing an equal reflectance are known, the following information can be obtained by obtaining three or more images while changing the light source direction.

[0345] Object information: normal direction vector and reflectance of each point on image

[0346] Light source information: light source direction vector and luminance from object observation point

[0347] Note however that the reflectance of the object and the luminance of the light source obtained through the above process are relative, and in order to obtain absolute values, there is needed known information different from the above, such as the reflectance being known for six or more points on the image.

[0348] As described above, with the photometric stereo method and the method using polarization characteristics, the surface normal information is obtained. On the other hand, with such methods as the slit-ray projection method or the stereo vision, 3-dimensional position information of the object is obtained. The object surface normal information is inclination information within a minute space of the 3-dimensional position information of the object, and they are both shape information of the object.

[0349] By the above process, the shape information obtaining section **305** obtains the surface normal information and the 3-dimensional position information of the object, which are shape information of the object.

[0350] By the above process, the following information are obtained.

[0351] Diffuse reflection image of object

[0352] Specular reflection image of object

[0353] 3-dimensional shape information of object

[0354] Light source position/illuminance

[0355] Then, the parameter estimation section **306** estimates, by a different method, each of the reflection parameters of the diffuse reflection component and the specular reflection component divided by the area dividing section **303**. First, the process for the diffuse reflection component will be described.

[0356] The parameter estimation section **306** estimates the albedo of the object by using the diffuse reflection area divided by the area dividing section **303**. Since the albedo is not influenced by the light source information, it is possible to realize a process that is robust against light source variations by performing a process using an albedo image.

[0357] This process will now be described. First, the reflection characteristics of an object will be described. Assuming a dichroic reflection model, the brightness of an object is expressed by the following expression as the sum of the diffuse reflection component and the specular reflection component.

[Exp. 35]

$$I=I_a+I_d+I_s \qquad \text{Expression 27}$$

[0358] Herein, I is the luminance value of the object of which an image is captured by the image capture device, I_a is the ambient light component, I_d is the diffuse reflection component, and I_s is the specular reflection component. Herein, the ambient light component refers to indirect light which is the light of the light source being scattered by objects, etc. This is scattered everywhere in the space, giving slight brightnesses even to shaded portions where direct light cannot reach. Therefore, it is usually often treated as noise.

[0359] Considering that the ambient light component is sufficiently small and is negligible as noise, an image can be separated into a diffuse reflection component and a specular reflection component.

[0360] From Expression 16, the following relationship holds for the diffuse reflection component.

Expression 28

$$\rho_{dp} = \frac{i_{f(p)}}{t_f \cdot \cos\theta_i} \quad \text{[Exp. 36]}$$

[0361] Herein, θ_i denotes the angle between the normal direction vector of the object and the light source direction vector. Herein, the angle θ_i is known from the light source information estimating section **304** and the shape information obtaining section **305**. Since the incident illuminance t_f of the light source can also be estimated, as will be described later, the albedo ρ_{dp} of the object can be obtained from Expression 28.

[0362] Instead of obtaining the albedo of the object, one may obtain and use a pseudo-albedo, which is the albedo multiplied by the radiation brightness of the light source, from the following expression.

$$t_f \cdot \rho_{dp} = \frac{i_{f(p)}}{\cos\theta_i} \quad \text{[Exp. 37]}$$

[0363] Next, the estimation of the reflection parameter for the specular reflection component will be described. The parameter estimation section **306** estimates parameters for expressing an object by using the normal information of the object obtained by the shape information obtaining section **305**, and the diffuse reflection image and the specular reflection image separated by the area dividing section **303**. Herein, a method using the Cook-Torrance model, which is widely used in the field of computer graphics, will be described.

[0364] With the Cook-Torrance model, a specular reflection image is modeled as shown in the following expressions.

Expression 29

$$I_s = K_s \rho_{s,\lambda} \quad \text{[Exp. 38]}$$

Expression 30

$$K_s = \frac{1}{\pi} E_i k_s \quad \text{[Exp. 39]}$$

-continued

Expression 31

$$\rho_{s,\lambda} = \frac{F_\lambda DG}{n \cdot V} \quad \text{[Exp. 40]}$$

Expression 32

$$F_\lambda = \frac{1}{2}\frac{(g_\lambda - c)^2}{(g_\lambda + c)^2}\left(1 + \frac{[c(g_\lambda + c) - 1]^2}{[c(g_\lambda - c) + 1]^2}\right) \quad \text{[Exp. 41]}$$

Expression 33

$$c = L \cdot H \quad \text{[Exp. 42]}$$

Expression 34

$$g_\lambda = \sqrt{n_\lambda^2 - 1 + c^2} \quad \text{[Exp. 43]}$$

Expression 35

$$D = \frac{1}{4m^2\cos^4\beta}\exp\left\{-\frac{\tan^2\beta}{m^2}\right\} \quad \text{[Exp. 44]}$$

Expression 36

$$G = \min\left\{1, \frac{2(n \cdot H)(n \cdot V)}{(V \cdot H)}, \frac{2(n \cdot H)(n \cdot L)}{(V \cdot H)}\right\} \quad \text{[Exp. 45]}$$

Expression 37

$$E_i = \sum_{j=0}^{n-1} I_j n \cdot L_j \quad \text{[Exp. 46]}$$

[0365] Herein, Ei denotes the incident illuminance, ρs,λ the bidirectional reflectance function of the specular reflection component for the wavelength λ, n the normal direction vector of the object, V the viewing vector, L the light source direction vector, H the half-way vector between the viewing vector and the illumination direction vector, and β the angle between the half-way vector H and the normal direction vector n (see FIG. **64**). Fλ denotes the Fresnel coefficient, which is the ratio of reflected light from the dielectric surface obtained from Fresnel equations, D the microfacet distribution function, and G the geometric attenuation factor representing the influence of shading due to roughness on the object surface. Moreover, nλ denotes the refractive index of the object, m a coefficient representing the roughness of the object surface, and I_j the luminance of the incident light. K_s denotes the coefficient of the specular reflection component.

[0366] Moreover, Expression 27 can be developed as follows by using the Lambertian model of Expression 16.

[Exp. 47]

$$I = I_a + I_d + I_s = I_a + K_D + K_s \rho_{s,\lambda} \quad \text{Expression 38}$$

[0367] where

Expression 39

$$K_D = \frac{1}{\pi} S_r E_i k_d \rho_d \quad \text{[Exp. 48]}$$

Expression 40

$$S_r = \frac{dpx \cdot dpy}{2\pi r^2} \quad \text{[Exp. 49]}$$

[0368] Herein, ρ_d denotes the reflectance (albedo) for the diffuse reflection component, dpx and dpy the lengths of one pixel of the image capture device, in the x direction and the y direction, respectively, and r the distance from the observation point O of the image capture device. K_d is a coefficient that satisfies the following mathematical relation.

[Exp. 50]

$$k_d+k_s=1 \qquad \text{Expression 41}$$

[0369] Sr is a constant representing the difference in luminance value between the diffuse reflection component and the specular reflection component, and indicates that the diffuse reflection component reflects an energy from the object in every direction. FIG. **65** is a schematic diagram illustrating the constant Sr. In FIG. **65**, the diffuse reflection component energy reflected at the observation point O spreads hemispherically. Herein, since the image capture device **601** is apart from the observation point O by r, the ratio S_r between the energy reaching one image sensor of the image capture device and the total energy reflected at the observation point O is expressed by Expression 40.

[0370] From the above, the parameter estimation section **306** estimates the reflection parameter of the specular reflection component from Expressions 29 to 40.

[0371] Combining these mathematical relationships together, known parameters for parameter estimation and parameters to be estimated are as follows:

[0372] (Known parameters)

[0373] Ambient light component I_a

[0374] Diffuse reflection component I_d

[0375] Specular reflection component I_s

[0376] Normal direction vector n of object

[0377] Light source direction vector L

[0378] Viewing vector V

[0379] Half-way vector H

[0380] Angle β between half-way vector H and normal direction vector n

[0381] Lengths dpx, dpy of one pixel of image capture device **601** in x, y direction

[0382] Distance r between image capture device **601** and observation point O

[0383] (Parameters to be estimated)

[0384] Incident illuminance Ei

[0385] Coefficient k_s of specular reflection component

[0386] Surface roughness m of object

[0387] Refractive index $\eta\lambda$ of object

[0388] Herein, the coefficient k_d of the diffuse reflection component and the reflectance (albedo) ρ_d of the diffuse reflection component are also unknown parameters, but these are not estimated so as to estimate only the parameters of the specular reflection component.

[0389] FIG. **66** is a chart showing the flow of the process performed by the parameter estimation section **306**. The process includes the following two steps.

[0390] First, the incident illuminance Ei is obtained by using the light source information (step S**701**). Herein, the process uses the light source position information obtained by the light source information estimating section **304**, the distance information between the image capture device and the object obtained by the shape information obtaining section **305**, and the light source illuminance obtained by the light source information obtaining section **304**. This can be obtained from the following expression.

Expression 41

$$E_i = \frac{R_1^2}{R_2^2} \cdot \frac{\cos\theta_1}{\cos\theta_2} \cdot I_i \qquad [\text{Exp. } 51]$$

[0391] It is assumed that the image capture device **601** is provided with the illuminometer **211**, as described above. Herein, I_i denotes the incident illuminance of the light source **602** measured by the illuminometer **211**, R_1 the distance between the image capture device **601** and the light source **602**, R_2 the distance between the light source **602** and the observation point O, θ_1 the angle between the normal direction vector n at the observation point O and the light source direction vector LC, and θ_2 the angle between the optical axis direction in the image capture device **601** and the light source direction vector LA (see FIG. **67**). Where it can be assumed that the size of the object is sufficiently smaller than the distance R_2 between the light source **602** and the observation point O, the distance R**2** will be equal at all the observation points O on the object. Therefore, (R_1/R_2) in Expression 42 becomes a constant, and no longer needs to be actually measured. θ_1 is known. This is because the normal direction vector n at the observation point O is known by the shape information obtaining section, and the light source direction vector LC is known by the light source information estimating section **304**. Moreover, θ_2 is known if the position of the light source is estimated by the light source information estimating section **304**. Therefore, the right side of Expression 42 is all known.

[0392] Next, the unknown parameters m, $\eta\lambda$ and k_s are estimated by using the simplex method (step S**702**). The simplex method is a method in which variables are assigned to vertices of a shape called a "simplex", and a function is optimized by changing the size and shape of the simplex (Noboru Ota, "Fundamentals Of Color Reproduction Optics", pp. 90-92, Corona Publishing Co., Ltd.). A simplex is a collection of (n+1) points in an n-dimensional space. Herein, n is the number of unknowns to be estimated and is herein "3". Therefore, the simplex is a tetrahedron. With vectors x_i representing the vertices of the simplex, new vectors are defined as follows.

Expression 43

$$x_h = \underset{x_i}{\operatorname{argmax}}\{f(x_i)\},\ i = 1, 2, \ldots, n+1 \qquad [\text{Exp. } 52]$$

$$x_s = \underset{x_i}{\operatorname{argmax}}\{f(x_i)\},\ i \neq h \qquad [\text{Exp. } 53]$$

$$x_l = \underset{x_i}{\operatorname{argmax}}\{f(x_i)\},\ i = 1, 2, \ldots, n+1 \qquad [\text{Exp. } 54]$$

Expression 44

$$x_0 = \sum \frac{x_i}{n+1},\ i \neq h,\ i = 1, 2, \ldots, n+1 \qquad [\text{Exp. } 55]$$

[0393] where

$$\underset{x_i}{\operatorname{argmax}}\{f(x_i)\}, \quad \text{[Exp. 56]}$$

$$\underset{x_i}{\operatorname{argmax}}\{f(x_i)\} \quad \text{[Exp. 57]}$$

[0394] denote x_i that maximizes and minimizes the function $f(x_i)$, respectively.

[0395] The three operations used in this method are defined as follows.

[0396] 1. Reflection:

[Exp. 58]

$$x_r=(1+\alpha)x_0-\alpha x_h \quad \text{Expression 45}$$

[0397] 2. Expansion:

[Exp. 59]

$$X_e=\beta x_r+(1-\beta)x_h \quad \text{Expression 46}$$

[0398] 3. Contraction:

[Exp. 60]

$$x_c=\gamma x_h+(1-\gamma)x_0 \quad \text{Expression 47}$$

[0399] Herein, $\alpha(>0)$, $\beta(>1)$ and $\gamma(1>\gamma>0)$ are coefficients.

[0400] The simplex method is based on the assumption that by selecting one of the vertices of the simplex that has the greatest function value, the function value in the reflection will be small. If this assumption is correct, it is possible to obtain the minimum value of the function by repeating the same process. Specifically, parameters given by initial values are updated by the three operations repeatedly until the error with respect to the target represented by the evaluation function becomes less than the threshold. Herein, m, η_λ and k_s are used as parameters, and the difference ΔI_s between the specular reflection component image calculated from Expression 29 and the specular reflection component image obtained by the area dividing section **303**, represented by Expression 48, is used as the evaluation function.

Expression 48

$$\Delta I_s = \sum_j \sum_i M_{s(i,j)}(i'_{s(i,j)} - i_{s(i,j)})^2 \quad \text{[Exp. 61]}$$

[0401] Herein, $i_{s(i,j)}'$ and $i_{s(i,j)}$ are the calculated specular reflection image estimate value I_s', and the luminance value of the pixel (i,j) of the specular reflection component image I_s obtained by the area dividing section **303**, and $M_{s(i,j)}$ is a function that takes 1 when the pixel (i,j) has a specular reflection component and 0 otherwise.

[0402] This process will now be described in detail. FIG. **68** is a flow chart illustrating the flow of this process.

[0403] First, the counters n and k for storing the number of times the updating operation has been repeated are initialized to 0 (step **S711**). The counter n is a counter for storing the number of times the initial value has been changed, and k is a counter for storing the number of times the candidate parameter has been updated by the simplex for an initial value.

[0404] Then, random numbers are used to determine the initial values of the candidate parameters m', η_λ' and k_s' of estimate parameters (step **S712**). Based on the physical constraints of the parameters, the range of initial values was determined as follows.

[Exp. 62]

$$m \geqq 0$$

$$\eta_\lambda \geqq 1.0$$

$$0 \leqq k_s \leqq 1.0$$

$$0 \leqq F_\lambda \leqq 1.0$$

$$0 \leqq D \quad \text{Expression 49}$$

[0405] Then, the obtained candidate parameters are substituted into Expression 29 to obtain the specular reflection image estimate value I_s' (step **S713**). Moreover, the difference ΔI_s between the calculated specular reflection image estimate value I_s' and the specular reflection component image obtained by the area dividing section **303** is obtained from Expression 48, and this is used as the evaluation function of the simplex method (step **S714**). If the obtained ΔI_s is sufficiently small (Yes in step **S715**), the candidate parameters m', η_λ' and k_s' are selected as the estimate parameters m, η_λ and k_s, assuming that the parameter estimation has been succeeded, and the process is ended. On the other hand, if ΔI_s is large (No in step **S715**), the candidate parameters are updated by the simplex method.

[0406] Before the candidate parameters are updated, the number of times update has been done is evaluated. First, 1 is added to the counter k storing the number of times update has been done (step **S716**), and the value of the counter k is judged (step **S717**). If the counter k is sufficiently large (No in step **S717**), it is determined that the operation has been repeated sufficiently, but the value has dropped to the local minimum and the optimal value will not be reached by repeating the update operation, and therefore the initial values are changed to attempt to escape from the local minimum. Therefore, 1 is added to the counter n and the counter k is set to 0 (step **S721**). It is determined whether the value of the counter n is higher than the threshold to thereby determine whether the process should be continued as it is or the process should be ended as being unprocessable (step **S722**). If n is greater than the threshold (No in step **S722**), the process is ended, determining that the image cannot be estimated. On the other hand, if n is smaller than the threshold (Yes in step **S722**), initial values are re-selected from random numbers within the range of Expression 49 (step **S712**) to repeat the process. Such a threshold for k may be, for example, 100, or the like. On the other hand, in step **S717**, if the counter k is less than or equal to the threshold (Yes in step **S717**), the candidate parameters are changed by using Expressions 45 to 47 (step **S718**). This process will be described later.

[0407] Then, it is determined whether the modified candidate parameters are meaningful as a solution (step **S719**). That is, the modified parameters may become physically meaningless values (for example, the roughness parameter m being a negative value) as the simplex method is repeated, and such a possibility is eliminated. For example, the following conditions may be given so that a parameter is determined to

be meaningful if it satisfies the condition and meaningless otherwise.

[Exp. 63]

$$0 \leqq m$$

$$1.0 \leqq \eta_\lambda$$

$$0.0 \leqq k_s \leqq 1.0$$

$$0.0 \leqq D$$

$$0.0 \leqq F_\lambda \leqq 1.0 \qquad \text{Expression 50}$$

[0408] These values can be obtained from the object. For example, the refractive index η_λ is a value determined by the material of the object. For example, it is known to be 1.5 to 1.7 for plastic and 1.5 to 1.9 for glass, and these values can be used. That is, if the object is plastic, the refractive index η_λ can be set to 1.5 to 1.7.

[0409] If the modified parameters satisfy Expression 50 (Yes in step S**719**), it can be assumed that the candidate parameters are meaningful values, and they are set as new candidate parameters (step S**720**), and the update process is repeated (step S**713**). On the other hand, if the modified parameters do not satisfy Expression 50 (No in step S**719**), the update process for the initial values is canceled, and the update is performed with new initial values (step S**721**).

[0410] The modifying process in step S**718** will now be described in detail. FIG. **69** is a flow chart showing the flow of the process. Herein, the candidate parameters m', η_λ' and k_s' are represented as a vector and it is used as the parameter x. That is,

[Exp. 64]

$$X=[m'\eta_{s,\lambda}'k_s']^T$$

[0411] First, by using Expression 43, Expression 44 and Expression 45, the parameter x_r having gone through the reflection operation is calculated, and Expression 48 is used to calculate the difference $\Delta I_s(x_r)$ with respect to the specular reflection component image with x_r (step S**731**). Then, the obtained $\Delta I_s(x_r)$ and $\Delta I_s(x_s)$ of which the evaluation function is the second worst are compared with each other (step S**732**). If $\Delta I_s(x_r)$ is smaller than $\Delta I_s(x_s)$ (Yes in step S**732**), the evaluation value $\Delta I_s(x_r)$ having gone through the reflection operation and $\Delta I_s(x_l)$ whose evaluation value is currently the best are compared with each other (step S**733**). If $\Delta I_s(x_r)$ is greater than or equal to $\Delta I_s(x_l)$ (No in step S**733**), x_h of which the evaluation value is lowest is changed to x_r (step S**734**), and the process is ended.

[0412] On the other hand, if $\Delta I_s(x_r)$ is smaller than $\Delta I_s(x_l)$ (Yes in step S**733**), Expression 46 is used to perform the expansion process and to calculate the difference $\Delta I_s(x_e)$ between the parameter x_e and the specular reflection component image with x_e (step S**735**). Then, the obtained $\Delta I_s(x_r)$ and $\Delta I_s(x_r)$ obtained by the reflection operation are compared with each other (step S**736**). If $\Delta I_s(x_e)$ is smaller than $\Delta I_s(x_r)$ (Yes in step S**736**), x_h of which the evaluation value is worst is changed to x_e (step S**737**), and the process is ended.

[0413] On the other hand, if $\Delta I_s(x_e)$ is greater than $\Delta I_s(x_r)$ (No in step S**736**), x_h of which the evaluation value is worst is changed to x_r (step S**734**), and the process is ended.

[0414] In step S**732**, if $\Delta I_s(x_r)$ is greater than $\Delta I_s(x_s)$ (No in step S**732**), the evaluation value $\Delta I_s(x_r)$ having gone through the reflection operation and $\Delta I_s(x_h)$ of which the evaluation value is currently worst are compared with each other (step S**738**). If $\Delta I_s(x_r)$ is smaller than $\Delta I_s(x_h)$ (Yes in step S**738**), x_h of which the evaluation value is worst is changed to x_r (step S**739**), and Expression 46 is used to calculate the difference $\Delta I_s(x_e)$ between the parameter x_e having gone through the contraction operation and the specular reflection component image with x_c (step S**740**). On the other hand, if $\Delta I_s(x_r)$ is greater than $\Delta I_s(x_h)$ (No in step S**738**), the difference $\Delta I_s(x_c)$ between the parameter x_c having gone through the contraction operation and the specular reflection component image with x_c is calculated (step S**740**) without changing x_h.

[0415] Then, the obtained $\Delta I_s(x_c)$ and $\Delta I_s(x_h)$ of which the evaluation value is worst are compared with each other (step S**741**). If $\Delta I_s(x_c)$ is smaller than $\Delta I_s(x_h)$ (Yes in step S**741**), x_h of which the evaluation value is worst is changed to x_c (step S**742**), and the process is ended.

[0416] On the other hand, if $\Delta I_s(x_c)$ is greater than $\Delta I_s(x_h)$ (No in step S**741**), all the candidate parameters x_i (i=1, 2, 3, 4) are changed as shown in the following expression, and the process is ended.

[Exp. 65]

$$x_i = \frac{1}{2}(x_i + x_l)$$

[0417] By repeating the process described above, m, η_λ and k_s, being unknown parameters in the specular reflection image, are estimated.

[0418] By the process described above, it is possible to estimate all the unknown parameters.

[0419] FIG. **70** is a graph representing the half-way vector p along the horizontal axis and the luminance value Is of the specular reflection component along the vertical axis, for the area C of FIG. **75**(*a*). In the graph, the open circular dots are obtained by plotting the luminance value Is observed for the area C. The solid squares are obtained by estimating and plotting the parameters of the Cook-Torrance model.

[0420] Note that FIG. **75**(*b*) is a graph obtained where a conventional area dividing approach is used, as described above. FIG. **76** shows a synthesized image produced by using a conventional area dividing approach. Thus, if the parameter estimation fails, the texture of the synthesized image will be substantially different from the actual texture.

[0421] From these figures, it can be seen that with the conventional area dividing approach, the separation precision between the specular reflection component and the diffuse reflection component is low, and the reflection parameter estimation has therefore failed. Therefore, the synthesized image will have a substantially different texture from that of the actual image, as shown in FIG. **76**. On the other hand, such a problem does not occur with the area dividing approach of the present invention.

[0422] The model used for the parameter estimation does not need to be the Cook-Torrance model, but may be, for example, the Torrance-Sparrow model, the Phong model, or the simplified Torrance-Sparrow model (for example, K. Ikeuchi and K. Sato, "Determining Reflectance Properties Of An Object Using Range And Brightness Images", IEEE Transactions on Pattern Analysis and Machine Intelligence, vol. 13, no. 11, pp. 1139-1153, 1991).

[0423] The parameter estimating method does not need to be the simplex method, but may be an ordinary parameter estimating method, such as, for example, the gradient method or the method of least squares.

[0424] The process described above may be performed for each pixel, or an equal set of parameters may be estimated for each of divided areas. Where the process is performed for each pixel, it is preferred to obtain samples in which known parameters such as the normal direction vector n of the object, the light source vector L or the viewing vector V are varied by moving the light source, the image capture device or the object. Where the process is performed for each area, it is preferred that the division of areas is changed so that variations in the parameters obtained for different areas are little so as to realize an optimal parameter estimation.

[0425] The parameter DB **307** stores, as model parameters, the reflection parameter for the diffuse reflection component and the reflection parameter for the specular reflection component obtained by the parameter estimation section **306**, and the shape information obtained by the shape information obtaining section **305**. FIG. **71** is a schematic diagram showing the model parameters stored in the parameter DB **307**.

[0426] By the above process, the parameter estimation device **300** estimates parameters of the diffuse reflection component and parameters of the specular reflection component, and stores the estimated parameter information in the parameter DB **307**.

[0427] Next, the image synthesis apparatus **301** will be described.

[0428] The viewpoint/light source information obtaining section **308** obtains the viewpoint and the light source information of an image to be synthesized. This may be done by the user inputting the viewpoint position, the light source position/light source illuminance, and the ambient light component information. Where a CG image is rendered on the real world, such as with the augmented reality, the light source information may be estimated by using the light source information estimating section **304**.

[0429] The rendering section **309** synthesizes an image according to the viewpoint and the light source information obtained by the viewpoint/light source information obtaining section **308** by using the model parameter information stored in the parameter DB **307**. The rendering section **309** separately renders the diffuse reflection component and the specular reflection component, and synthesizes an image by combining together the rendered diffuse reflection component, the rendered specular reflection component, and the ambient light component information.

[0430] First, the process will be described for the diffuse reflection component. As described above, an albedo image is what is obtained by dividing the diffuse component image by the inner product between the light source vector and the normal direction vector of the object. Thus, the diffuse reflection component can be synthesized by using the light source direction vector information obtained by the viewpoint/light source information obtaining section **308**, together with the albedo image (estimated by the parameter estimation section **306**) and the shape information (obtained by the shape information obtaining section **305**) stored in the parameter DB. Specifically, the diffuse component image is synthesized by obtaining the inner product between the light source direction vector obtained by the viewpoint/light source information obtaining section **308** and the normal direction vector of the object, and further multiplying it with the albedo image. Where a plurality of light sources are input from the viewpoint/light source information obtaining section **308**, the process synthesizes a diffuse reflection component image for each of the light sources and combines together the images to synthesize a single diffuse reflection component image.

[0431] Next, the process for the specular reflection component will be described. The specular reflection component can be synthesized by using the light source direction vector information obtained by the viewpoint/light source information obtaining section **308**, together with the specular reflection parameter (estimated by the parameter estimation section **306**) and the shape information (obtained by the shape information obtaining section **305**) stored in the parameter DB. Specifically, the specular reflection component image is synthesized by substituting the estimated parameters into Expressions 29 to 37.

[0432] The rendering section **309** synthesizes an image according to the viewpoint and the light source information obtained by the viewpoint/light source information obtaining section **308** by synthesizing together the diffuse reflection component image and the specular reflection component image, thus obtained, and the ambient light component information obtained by the viewpoint/light source information obtaining section **308**.

[0433] As described above, by using the area dividing method of the present invention, it is possible to perform, with a high precision, a model-based image synthesis used in digital archives, etc.

INDUSTRIAL APPLICABILITY

[0434] With the image process of the present invention, it is possible to more accurately separate between a specular reflection area and a diffuse reflection area by using two kinds of information, i.e., the light source condition dependency and the polarization information. Since an area dividing process can be achieved with an image that is captured as if taking a snapshot, the present invention is useful for various types of digital still cameras, digital camcorders and surveillance cameras.

REFERENCE SIGNS LIST

[0435] **101** illumination section
[0436] **102** illumination control section
[0437] **103** polarization image capturing section
[0438] **104** polarization information obtaining section
[0439] **105** light source dependency estimation section
[0440] **106** area dividing section
[0441] **107** captured image determination section.
[0442] **108** illumination device
[0443] **109** area dividing device
[0444] **110** communication section
[0445] **111** communication section
[0446] **112** illumination position changing section
[0447] **120** control section
[0448] **121** illumination unit
[0449] **122** polarization information obtaining section

1. An image processing apparatus for capturing an image of an object and thereby performing an optical area division of a surface of the object, comprising:

a polarization image capturing section for obtaining a polarization image of the object by receiving light having passed through a three-way or more polarizer having different polarization main axis angles,

wherein the area division is performed based on a polarization state on the surface of the object and a light source dependency, which represents a degree of change

in the polarization state on the surface of the object occurring when changing at least one of a polarization state of light emitted from a light source and a light source position.

2. The image processing apparatus according to claim **1**, comprising:

an illumination unit including the light source and being capable of changing at least one of the polarization state of light emitted from the light source and the light source position; and

a control section for synchronizing the changing by the illumination unit of at least one of the polarization state of light emitted from the light source and the light source position with the image-capturing by the polarization image capturing section.

3. The image processing apparatus according to claim **2**, comprising:

an illumination control section for changing the polarization state of light emitted from the light source;

a polarization information obtaining section for generating, from the obtained polarization image, polarization information for received polarized light by using a correspondence with a brightness of the light having passed through the three-way or more polarizer, for each of unit pixels of the polarization image;

a light source dependency estimation section for estimating light source dependency information by making a comparison between the polarization information generated by the polarization information obtaining section when the polarization state of light emitted from the light source is changed by the illumination control section; and

an area dividing section for performing the area division based on the polarization information generated by the polarization information obtaining section and light source variation information estimated by the light source dependency estimation section.

4. The image processing apparatus according to claim **3**, wherein the polarization information obtaining section generates, as the polarization information, at least one of a degree of polarization, a polarization phase, a polarization estimation error, a polarization maximum luminance value, and a polarization minimum luminance value.

5. The area dividing device according to claim **4**, wherein the area dividing section performs the area division so that the surface of the object is divided into areas each being a diffuse reflection area or a specular reflection area.

6. The image processing apparatus according to claim **4**, wherein the area dividing section performs the area division so that the surface of the object is divided into areas each being a diffuse reflection non-polarized area, a diffuse reflection polarized area, or a specular reflection polarized area.

7. The image processing apparatus according to claim **4**, wherein the area dividing section performs the area division so that the surface of the object is divided into areas each being a light source-dependent polarized area, a light source-dependent non-polarized area, a light source-independent polarized area, or a light source-independent non-polarized area.

8. The image processing apparatus according to claim **2**, comprising:

an illumination position changing section for changing the position of the light source;

a polarization information obtaining section for generating, from the obtained polarization image, polarization information for received polarized light by using a correspondence with a brightness of the light having passed through the three-way or more polarizer, for each of unit pixels of the polarization image;

a light source dependency estimation section for estimating light source dependency information by making a comparison between the polarization information generated by the polarization information obtaining section when the position of the light source is changed by the illumination control section; and

an area dividing section for performing the area division based on the polarization information generated by the polarization information obtaining section and light source variation information estimated by the light source dependency estimation section.

9. The image processing apparatus according to claim **8**, comprising:

a plurality of illumination sections of different light source positions,

wherein the illumination position changing section changes a position of illumination section by switching between the plurality of illumination sections.

10. The image processing apparatus according to claim **8**, wherein the illumination position changing section changes the light source position by moving an illumination section.

11. The image processing apparatus according to claim **8**, wherein the area dividing section performs the area division so that the surface of the object is divided into areas each being a diffuse reflection area or a specular reflection area.

12. The image processing apparatus according to claim **8**, wherein the area dividing section performs the area division so that the surface of the object is divided into areas each being a specular reflection area, a diffuse reflection area, or a shaded area.

13. An image processing system comprising an illumination device and an area dividing device for capturing an image of an object and thereby performing an optical area division of a surface of the object,

the illumination device comprising:

an illumination section for emitting linearly-polarized light onto the object; and

an illumination control section for changing a polarization state of the linearly-polarized light of the illumination section,

the area dividing device comprising:

a polarization image capturing section for obtaining a polarization image of the object by receiving light having passed through a three-way or more polarizer having different polarization main axis angles;

a captured image determination section for comparing a polarization image captured in a past by the polarization image capturing section with a currently-captured polarization image to thereby determine whether the captured polarization states have changed sufficiently;

a polarization information obtaining section for generating, from the obtained polarization image, polarization information for received polarized light by using a correspondence with a brightness of the light having passed through the three-way or more polarizer, for each of unit pixels of the polarization image;

a light source dependency estimation section for estimating a light source dependency information by making a

comparison between the polarization information generated by the polarization information obtaining section when it is determined by the captured image determination section that the polarization state of the illumination section has been changed by the illumination control section; and

an area dividing section for performing the area division by using the polarization information generated by the polarization information obtaining section and light source variation information estimated by the light source dependency estimation section.

14. An image processing system comprising an illumination device and an area dividing device for capturing an image of an object and thereby performing an optical area division of a surface of the object,

the illumination device comprising:

an illumination section for emitting linearly-polarized light onto the object;

an illumination control section for changing a polarization state of the linearly-polarized light of the illumination section; and

a communication section for transmitting a signal indicating a light emission to the area dividing device and receiving a signal indicating a completion of image-capturing from the area dividing device,

the area dividing device comprising:

a communication section for receiving a signal indicating a light emission from the illumination device and transmitting a signal indicating a completion of image-capturing to the illumination device;

a polarization image capturing section for obtaining a polarization image of the object by receiving light having passed through a three-way or more polarizer having different polarization main axis angles;

a captured image determination section for comparing a polarization image captured in a past by the polarization image capturing section with a currently-captured polarization image to thereby determine whether the captured polarization states have changed sufficiently;

a polarization information obtaining section for generating, from the obtained polarization image, polarization information for received polarized light by using a correspondence with a brightness of the light having passed through the three-way or more polarizer, for each of unit pixels of the polarization image;

a light source dependency estimation section for estimating light source dependency information by making a comparison between the polarization information generated by the polarization information obtaining section when it is determined by the captured image determination section that the polarization state of the illumination section has been changed by the illumination control section; and

an area dividing section for performing the area division by using the polarization information generated by the polarization information obtaining section and light source variation information estimated by the light source dependency estimation section.

15. An area dividing method for capturing an image of an object and thereby performing an optical area division of a surface of the object, comprising:

an illumination step of emitting linearly-polarized light onto the object;

an illumination control step of changing a polarization state of the linearly-polarized light of the illumination section;

a polarization image capturing step of obtaining a polarization image of the object by receiving light having passed through a three-way or more polarizer having different polarization main axis angles;

a polarization information obtaining step of generating, from the obtained polarization image, polarization information for received polarized light by using a correspondence with a brightness of the light having passed through the three-way or more polarizer, for each of unit pixels of the polarization image;

a control step of synchronizing the illumination control step with the polarization image capturing step;

a light source dependency estimation step of estimating light source dependency information by making a comparison between the polarization information generated by the polarization information obtaining step when the polarization state of the illumination step is changed by the illumination control step; and

an area dividing step of performing the area division by using the polarization information generated by the polarization information obtaining step and light source variation information estimated by the light source dependency estimation step.

16. A program for an area dividing device for capturing an image of an object and thereby performing an optical area division of a surface of the object,

wherein the program instructs a computer to perform steps included in the area dividing method according to claim **15**.

17. A model-based image synthesis device comprising a parameter estimation device and an image synthesis apparatus for synthesizing an image using a reflection model,

the parameter estimation device comprising:

an image capturing section for capturing an image of an object;

an area dividing section for performing an optical area division of an image captured by the image capturing section according to the area dividing method according to claim **15**;

a light source information estimating section for estimating light source information regarding a light source illuminating the object;

a shape information obtaining section for obtaining, as shape information, surface normal information or 3-dimensional position information of the object;

a parameter estimation section for estimating a reflection model parameter by modeling the light source information estimated by the light source information estimating section for each area divided by the area dividing section and the shape information obtained by the shape information obtaining section, from the captured image of the object; and

a parameter database for storing the reflection parameter estimated by the parameter estimation section,

the image synthesis apparatus comprising:

a viewpoint/light source information obtaining section for obtaining a viewpoint or light source information of an image to be synthesized; and

a rendering section for synthesizing an image according to the viewpoint or light source information obtained by

the viewpoint/light source information obtaining section by using the reflection parameter information stored in the parameter database.

18. A model-based image synthesis method comprising a parameter estimation step and an image synthesis method step for synthesizing an image using a reflection model,

the parameter estimation step comprising:

an image capturing step of capturing an image of an object;

an area dividing step of performing an optical area division of an image captured by the image capturing section according to the area dividing method according to claim **15**;

a light source information estimating step of estimating light source information regarding a light source illuminating the object;

a shape information obtaining step of obtaining, as shape information, surface normal information or 3-dimensional position information of the object; and

a parameter estimation step of estimating a reflection model parameter by modeling the light source information estimated by the light source information estimating section for each area divided by the area dividing section and the shape information obtained by the shape information obtaining section, from the captured image of the object,

the image synthesis step comprising:

a viewpoint/light source information obtaining step of obtaining a viewpoint or light source information of an image to be synthesized; and

a rendering step of synthesizing an image according to the viewpoint or light source information obtained by the viewpoint/light source information obtaining section by using reflection parameter information estimated by the shape information obtaining step.

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