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Electronic Theatre Controls, Inc. d/b/a ETC

UNITED STATES DISTRICT COURT

CENTRAL DISTRICT OF CALIFORNIA

ELECTRONIC THEATRE CONTROLS, INC. d/b/a ETC, a Wisconsin Corporation,

Plaintiff,

v.

ELATION LIGHTING, INC., a Nevada Corporation,

Defendant.

CASE NO.: 2:25-cv-00852

COMPLAINT FOR PATENT INFRINGEMENT

DEMAND FOR JURY TRIAL

Plaintiffs Electronic Theatre Controls, Inc. d/b/a ETC, by way of this Complaint against Defendant Elation Lighting, Inc., allege as follows:

THE PARTIES

1. Plaintiff Electronic Theatre Controls, Inc. d/b/a ETC ("ETC") is a Wisconsin corporation, with its principal place of business located at 3031 Pleasant View Road, Middleton, WI 53562.

2. ETC is a leading supplier of lighting products and control systems for theatrical applications.

3. On information and belief, Defendant Elation Lighting, Inc. ("Elation") is a Nevada corporation having a principal place of business at 6122 S. Eastern Avenue, Los Angeles, California.

JURISDICTION AND VENUE

4. This is a civil action for patent infringement arising under the patent laws of the United States, 35 U.S.C. § 1 *et. seq.*, including 35 U.S.C. § 271, arising from Elation's actions, including making, using, selling, offering for sale and/or importing into the United States one or more products that infringe U.S. Patent Nos. 8,593,074 ("the '074 patent"), 11,240,898 ("the '898 patent"), and 11,849,519 ("the '519 patent"), including, without limitation, the Fuze Teatro light fixture (the "Accused Products"). This Court has subject matter jurisdiction under 28 U.S.C. §§ 1331 and 1338(a).

5. This Court has personal jurisdiction over Defendant because Defendant engages in business within this district, including having its principal place of business in this district, and has made, used, offered to sell and sold the Accused Products in this District.

6. Venue is proper in this district under 28 U.S.C. § 1400(b) because the Defendant has regular and established place of business in this district and has committed acts of infringement in this district.

BACKGROUND

7. ETC is the sole owner of the ‘074 patent, the ‘898 patent, and the ‘519 patent (collectively, the “ETC Patents”).

8. The ‘074 patent is titled “Systems and methods for controlling an output of a light fixture” was duly and legally issued by the United States Patent and Trademark Office on November 26, 2013. A true and complete copy of the ‘074 patent is attached hereto as Exhibit A. The ‘074 patent is valid and enforceable.

9. The ‘898 patent is titled “Systems, methods, and devices for influencing spectral content of a light output” and was duly and legally issued by the United States Patent and Trademark Office on February 1, 2022. A true and complete copy of the ‘898 patent is attached hereto as Exhibit B. The ‘898 patent is valid and enforceable.

10. The ‘519 patent is titled “Systems, methods, and devices for influencing spectral content of a light output” was duly and legally issued by the United States Patent and Trademark Office on December 19, 2023. A true and complete copy of the ‘519 patent is attached hereto as Exhibit C. The ‘519 patent is valid and enforceable.

11. As the owner of the ETC Patents, ETC is authorized and has standing to bring legal action to enforce all rights arising from the ETC Patents.

12. Plaintiff notified Defendant of its infringement of the ETC Patents on November 20, 2024.

13. Defendant has had constructive knowledge of infringement at least by virtue of ETC complying with 35 U.S.C. §287 by marking substantially all associated patented products with the website at www.etcconnect.com/IP/, which lists those products as being covered by the ETC Patents.

14. Defendant has had actual knowledge of the ETC patents and infringement of that no later than November 20, 2024.

COUNT I

Patent Infringement of the ‘074 patent

15. ETC realleges and incorporates the foregoing paragraphs as though fully set forth herein.

16. ETC has the right to enforce the ‘074 patent and right to recover damages for infringement.

17. Elation has directly infringed one or more claims of the ‘074 patent by making, using, offering to sell and/or importing the Accused Products.

18. With knowledge of the ‘074 patent, Elation has induced infringement of one or more claims of the ‘074 patent by actively encouraging others to make, use, offer to sell, sell and/or import the Accused Products knowing that such encouragement would result in direct infringement by others.

19. With knowledge of the ‘074 patent, Elation has contributed to infringement of one or more claims of the ‘074 patent by providing the Accused Products to others knowing that the Accused Products are a material part of the invention and especially made for use in a manner that infringes the ‘074 patent, and not a staple article or commodity of commerce suitable for substantial noninfringing use.

20. By way of example, the Accused Products infringe claim 14 of the ‘074 patent.

21. Claim 14 of the ‘074 patent states:

> 14. A system for controlling the output of a light fixture, the system including:
>
> four or more light sources; and
> a controller configured to
>
> receive a first input parameter corresponding to a first color point within a color space,

> receive a second input parameter associated with a desired intensity for the first color point,
>
> determine a white point based on a relationship between the second input parameter and the color temperature of a black-body radiator, the white point corresponding to a second color point within the color space,
>
> select a color temperature transform based on the white point,
>
> calculate a third color point within the color space based on the color temperature transform, the color temperature transform defining a relationship between the first color point and the third color point, the third color point being different than the first color point, and the third color point being different than the second color point,
>
> determine a respective light source output value for each of the four or more light sources based on the third color point, and
>
> drive each of the four or more light sources at the respective light source output value to produce the output of the light fixture.

22. The Accused Products include all limitations of claim 14 of the ‘074 patent.

23. The Accused Products are a system for controlling the output of a light fixture.

24. The Accused Products include four or more light sources. Specifically, the Accused Products have at least red, green blue, mint and amber LED light sources.

25. The Accused Product includes a controller.

26. The controller of Accused Products is configured to receive a first input parameter corresponding to a first color point within a color space. For example, Accused Products are configured to receive a DMX value corresponding to a selected color point within a color space.

27. The controller of Accused Products is configured to receive a second input parameter associated with a desired intensity for the first color point by receiving a DMX value corresponding to a selected intensity for the first color point.

28. On information and belief, the controller of Accused Products is configured determine a white point based on a relationship between the second input parameter and the color temperature of a black-body radiator, the white point corresponding to a second color point within the color space.

29. On information and belief, the controller of Accused Products is configured to select a color temperature transform based on the white point as the intensity of the first color point is changed during dim-to-warm control.

30. On information and belief, the controller of Accused Products is configured to calculate a third color point within the color space based on the color temperature transform, the color temperature transform defining a relationship between the first color point and the third color point, the third color point being different than the first color point, and the third color point being different than the second color point.

31. On information and belief, the controller of Accused Products is configured to determine a respective light source output value for each of the four or more light sources based on the third color point.

32. On information and belief, the controller of Accused Products is configured to drive each of the four or more light sources at the respective light source output value to produce the output of the light fixture.

33. Elation knew that making, using, offering to sell, selling, and/or importing the Accused Products and instructing others to use the Accused Products in an infringing manner would infringe the ‘074 patent and that use of the Accused Products would contribute to direct infringement by another. Elation’s past and continued infringement of the ‘074 patent has been and continues to be willful and deliberate.

34. Because of Elation’s infringement of the ‘074 patent, ETC has suffered and will continue to suffer irreparable harm and monetary damages, which continue to accrue, in an amount to be determined at trial.

35. Elation’s willful infringement will continue unless enjoined by this Court.

COUNT II

Patent Infringement of the ‘898 patent

36. ETC realleges and incorporates the foregoing paragraphs as though fully set forth herein.

37. ETC has the right to enforce the ‘898 patent and right to recover damages for infringement.

38. Elation has directly infringed one or more claims of the ‘898 patent by making, using, offering to sell and/or importing the Accused Products.

39. With knowledge of the ‘898 patent, Elation has induced infringement of one or more claims of the ‘898 patent by actively encouraging others to make, use, offer to sell, sell and/or import the Accused Products knowing that such encouragement would result in direct infringement by others.

40. With knowledge of the ‘898 patent, Elation has contributed to infringement of one or more claims of the ‘898 patent by providing the Accused Products to others knowing that the Accused Products are a material part of the invention and especially made for use in a manner that infringes the ‘898 patent,

and not a staple article or commodity of commerce suitable for substantial noninfringing use.

41. By way of example, Elation's and others use of the Accused Products infringes claim 1 of the '898 patent.

42. Claim 1 of the '898 patent states:

> 1. A method for control of a light fixture, the method comprising:
>
> energizing the light fixture to produce a first light output with a first chromaticity and a first spectral power distribution;
>
> receiving a user input representative of a desired adjustment of a lighting effect;
>
> generating a target spectrum based on the user input; and
>
> energizing the light fixture to produce a second light output with the first chromaticity and a second spectral power distribution, the second power distribution approximates the target spectrum.

43. The Accused Products provide a method for control of light fixture. The Accused Products are a light fixture that is controlled by a user.

44. When used, the Accused products are energized to produce a first light output with a first chromaticity and a first spectral power distribution. For example, a user of the Accused Products can send a specific DMX value to a specific channel to select a correlated color temperature at a default (brightest) output.

45. The Accused Products receive a user input that represents a desired adjustment of a lighting effect (e.g., light quality). For example, from the brightest output setting, the Accused Products can receive a DMX value to select a balanced or a fidelity output setting.

46. The Accused Products generate a target spectrum based on the user input. For example, Elation touts that the Accused Products "allow[] user to select between Highest Output, Highest Fidelity, or a blend of both," that selection results in the generation of the target spectrum.

47. The Accused Products are further energized to produce a second light output with the first chromaticity and a second spectral power distribution, the second power distribution approximates the target spectrum. For example, when starting with the default brightest output, a user of the Accused Products may cause the Accused Products to produce a second light output, such as fidelity output or balanced output, at the first chromaticity, and cause the Accused Products to produce a corresponding spectral power that is different from the default brightest output (i.e., first spectral power distribution). The second power distribution approximates the target spectrum.

48. Elation also infringes claim 20, among other claims, of the '898.

49. Claim 20 of the '898 patent states:

> 20. A controller for controlling a light output of a light fixture,
>
> the controller including a non-transitory computer readable medium and a processor,
>
> the controller including computer executable instructions stored in the computer readable medium for controlling operation of the controller to:
>
> > energize the light fixture to produce a first light output with a first chromaticity and a first spectral power distribution;
> >
> > receive an input representative of an adjustment of a lighting effect;
> >
> > generate a target spectrum based on the user input; and
> >
> > energize the light fixture to produce a second light output with the first chromaticity and a second spectral power distribution,
> >
> > the second power distribution approximates the target spectrum.

50. The Accused Products include a controller for controlling the light output of a light fixture, i.e., Accused Products comprise a light fixture.

51. The controller of the Accused Products includes a non-transitory computer readable medium, i.e., a storage device.

52. The controller of the Accused Products includes a processor.

53. The controller of the Accused Products includes computer executable instructions, i.e., software, stored in the computer readable medium for controlling operation of the controller.

54. The controller of the Accused Products energizes the light fixture to produce a first light output with a first chromaticity and a first spectral power distribution.

55. The controller of the Accused Products receives an input representative of an adjustment of a lighting effect (e.g., light quality). For example, from the brightest output setting, the Accused Products can receive a DMX value to select a balanced or fidelity output setting.

56. The controller of the Accused Products generates a target spectrum based on the input. For example, the controller of the Accused Products is configured to generate a target spectrum corresponding to the brightest, fidelity and balanced output settings, whichever is selected according to the input.

57. The controller of the Accused Products controls the light source to produce a second light output with the first chromaticity and a second spectral power distribution, the second power distribution approximating the target spectrum. For example, when starting from the brightest output, changing the Accused Products to the fidelity or balanced output will produce a different (second) spectral power distribution with the first chromaticity. The second power distribution approximates the target spectrum.

58. The controller of the Accused Products energizes the light fixture to produce a second light output with the first chromaticity and a second spectral

power distribution, the second power distribution approximates the target spectrum. For example, when starting with the default brightest output, the controller of the Accused Products energizes the light fixture to produce a second light output, such as fidelity or balanced output, at the first chromaticity and a second spectral power that is different from the default brightest output (i.e., first spectral power distribution). The second power distribution approximates the target spectrum.

59. Elation knew that making, using, offering to sell, selling, and/or importing the Accused Products and instructing others to use the Accused Products in an infringing manner would infringe the ‘898 patent. Elation’s past and continued infringement of the ‘898 patent has been and continues to be willful and deliberate.

60. Because of Elation’s infringement of the ‘898 patent, ETC has suffered and will continue to suffer irreparable harm and monetary damages, which continue to accrue, in an amount to be determined at trial.

61. Elation’s willful infringement will continue unless enjoined by this Court.

COUNT III

Patent Infringement of the ‘519 patent

62. ETC realleges and incorporates the foregoing paragraphs as though fully set forth herein.

63. ETC has the right to enforce the ‘519 patent and right to recover damages for infringement.

64. Elation has directly infringed one or more claims of the ‘519 patent by making, using, offering to sell and/or importing the Accused Products.

65. With knowledge of the ‘519 patent, Elation has induced infringement of one or more claims of the ‘519 patent by actively encouraging others to make,

use, offer to sell, sell and/or import the Accused Products knowing that such encouragement would result in direct infringement by others.

66. With knowledge of the ‘519 patent, Elation has contributed to infringement of one or more claims of the ‘519 patent by providing the Accused Products to others knowing that the Accused Products are a material part of the invention and especially made for use in a manner that infringes the ‘519 patent, and not a staple article or commodity of commerce suitable for substantial noninfringing use.

67. By way of example, Elation’s and others’ use of the Accused Products infringes claim 1 of the ‘519 patent.

68. Claim 1 of the ‘519 patent states:

> 1. A lighting control system comprising:
>
> one or more light sources;
>
> one or more driver circuits configured to provide drive signals to the one or more light sources;
>
> an interface configured to receive an input related to a light output of the one or more light sources, the input being related to an adjustment of a lighting effect; and
>
> a controller connected to the one or more driving circuits and the interface, the controller including a processor and a memory, the controller configured to:
>
> > control the one or more light sources to produce a first light output with a first chromaticity and a first spectral power distribution,
> > receive the input related to the adjustment of the lighting effect,
> >
> > generate a target spectrum based on the input, and

> control the one or more light sources to produce a second light output with the first chromaticity and a second spectral power distribution, the second power distribution approximating the target spectrum.

69. The Accused Products are part of lighting control system.

70. The Accused Products have one or more light sources, including red, green blue, mint and amber LEDs.

71. The Accused Products have one or more driver circuits configured to provide drive signals to the light sources that control the output of the light sources.

72. The Accused Products include an interface configured to receive an input related to light out of the one or more light sources, the input being related to an adjustment of a lighting effect (e.g., light quality). For example, the Accused Products are part of a system that includes an interface in which the interface receives inputs from the user relating to the output from the light sources, the input being related to an adjustment of a lighting effect, such as selecting the brightest, balanced and fidelity output settings.

73. The Accused Products have a controller with a processor and memory connected to the driving circuits.

74. The controller of the Accused Products is configured to control the light sources to produce a first light output with a first chromaticity, i.e., a selected color and output setting (e.g., brightest) having a spectral power distribution for the selected color.

75. The controller of the Accused Products is configured to receive the input related to the adjustment of the lighting effect. For example, starting from the brightest output, a DMX signal can be sent to and received by the controller to adjust the lighting effect to, for example, the fidelity or the balanced output setting.

76. The controller of the Accused Products is configured to generate a target spectrum based on the input. For example, the controller of the Accused Products is configured to generate a target spectrum corresponding to the brightest, fidelity and balanced output settings, whichever is selected according to the input.

77. The controller of the Accused Products is configured to control the one or more light sources to produce a second light output with the first chromaticity and a second spectral power distribution, the second power distribution approximating the target spectrum. For example, when starting from the brightest output, changing the Accused Products to the fidelity or balanced output will produce a different (second) spectral power distribution with the first chromaticity. The second power distribution approximates the target spectrum.

78. The Accused Product also infringe claim 19, among other claims, of the ‘519 patent.

79. Claim 19 of the ‘519 patent states:

> 19. A controller for controlling a light output of a light source,
>
> the controller including a non-transitory computer readable medium and a processor,
>
> the controller including computer executable instructions stored in the computer readable medium for controlling operation of the controller to:
>
> control the light source to produce a first light output with a first chromaticity and a first spectral power distribution;
>
> receive an input related to an adjustment of a lighting effect;
>
> generate a target spectrum based on the input; and
>
> control the light source to produce a second light output with the first chromaticity and a second spectral power distribution, the second power distribution approximating the target spectrum.

80. The Accused Products include a controller for controlling the light output of light source, i.e., the five LEDs of the Accused Products.

81. The controller of the Accused Products includes a non-transitory computer readable medium, i.e., a storage device.

82. The controller of the Accused Products includes a processor.

83. The controller of the Accused Products includes computer executable instructions, i.e., software, stored in the computer readable medium for controlling operation of the controller.

84. The controller of the Accused Products controls the light source to produce a first light output with a first chromaticity and a first spectral power distribution.

85. The controller of the Accused Products receives an input related to an adjustment of a lighting effect (e.g., light quality), such as selecting the brightness, fidelity and balanced output settings.

86. The controller of the Accused Products generates a target spectrum based on the input. For example, the controller of the Accused Products is configured to generate a target spectrum corresponding to the brightest, fidelity and balanced output settings, whichever is selected according to the input.

87. The controller of the Accused Products controls the light source to produce a second light output with the first chromaticity and a second spectral power distribution, the second power distribution approximating the target spectrum. For example, when starting from the brightest output, changing the Accused Products to the fidelity or balanced output will produce a different (second) spectral power distribution with the first chromaticity. The second power distribution approximates the target spectrum.

88. Elation knew that making, using, offering to sell, selling, and/or importing the Accused Products and instructing others to use the Accused Products in an infringing manner would infringe the ‘519 patent. Elation’s past and

continued infringement of the ‘519 patent has been and continues to be willful and deliberate.

89. Because of Elation’s infringement of the ‘519 patent, ETC has suffered and will continue to suffer irreparable harm and monetary damages, which continue to accrue, in an amount to be determined at trial.

90. Elation’s willful infringement will continue unless enjoined by this Court.

PRAYER FOR RELIEF

WHEREFORE, ETC respectfully prays that upon trial on the merits this Court render judgment in ETC’s favor and against Elation as follows:

A. Judgment that Elation has infringed the ‘074 patent, the ‘898 patent, and the ‘519 patent under 35 U.S.C. § 271;

B. A preliminary and permanent injunction pursuant to 35 U.S.C. § 283, preventing Elation, its officers, agents, servants, employees, successors, assignees, parents, subsidiaries, affiliated or related companies, attorneys, and all others in active concert or participation with any of them from further infringing the ‘074 patent, the ‘898 patent, and the ‘519 patent;

C. An award of damages adequate to compensate ETC for Elation’s patent infringement, and no less than the damages provided under 35 U.S.C. § 284;

D. An award for enhanced damages under 35 U.S.C. § 284;

E. An award for attorneys’ fees under 35 U.S.C. § 285;

F. An award of pre-judgment interest, post-judgment interest, and all costs associated with this action; and

G. Any other relief as the Court deems appropriate and just under the circumstances.

JURY TRIAL DEMAND

ETC demands a trial by jury on all matters and issues properly tried to a jury pursuant to Federal Rules of Civil Procedure 38 and 39, and other applicable federal and state law.

Dated: January 31, 2025

SHANE A. BRUNNER
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MITCHELL SILBERBERG & KNUPP LLP

By: *_/s/ Karin G. Pagnanelli___________*
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Attorneys for Plaintiff
Electronic Theatre Controls, Inc. d/b/a ETC

Exhibit A

US008593074B2

(12) **United States Patent**
Hatley et al.

(10) **Patent No.: US 8,593,074 B2**
(45) **Date of Patent: Nov. 26, 2013**

(54) **SYSTEMS AND METHODS FOR CONTROLLING AN OUTPUT OF A LIGHT FIXTURE**

(75) Inventors: **Troy Bryan Hatley**, Lodi, WI (US); **Timothy George Robbins**, Lodi, WI (US); **Mike Wood**, Austin, TX (US)

(73) Assignee: **Electronic Theater Controls, Inc.**, Middleton, WI (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 445 days.

(21) Appl. No.: **13/004,922**

(22) Filed: **Jan. 12, 2011**

(65) **Prior Publication Data**

US 2012/0176063 A1 Jul. 12, 2012

(51) **Int. Cl.**
H05B 37/00 (2006.01)

(52) **U.S. Cl.**
USPC **315/291**; 315/307; 315/308; 315/312

(58) **Field of Classification Search**
USPC 315/291, 307, 308, 312, 314, 316, 319, 315/317, 318
See application file for complete search history.

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Primary Examiner — David H Vu
(74) *Attorney, Agent, or Firm* — Michael Best & Friedrich LLP

(57) **ABSTRACT**

Systems and methods for controlling an output of a light fixture. A light fixture of one construction includes four or more light sources and is configured to produce an output that mimics the color temperature changes of an ideal black-body radiator based on one or more input parameters. The input parameters correspond to, for example, a desired target color and an intensity for the desired target color. A white point setting is determined based on the one or more input parameters and a relationship between the one or more input parameters and the color temperature of an ideal black-body radiator. A color temperature transform is selected based on the white point color temperature setting, and is used to determine a color coordinate corresponding to a modified target color. A set of light source output values corresponding to the modified target color are identified, and the light sources are driven to the identified output values.

20 Claims, 9 Drawing Sheets

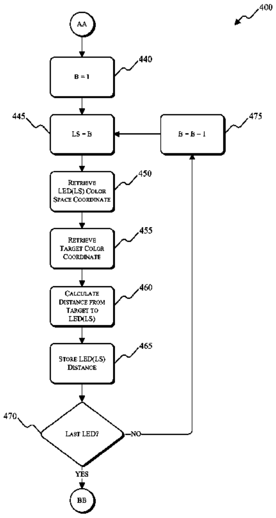

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FIG. 1

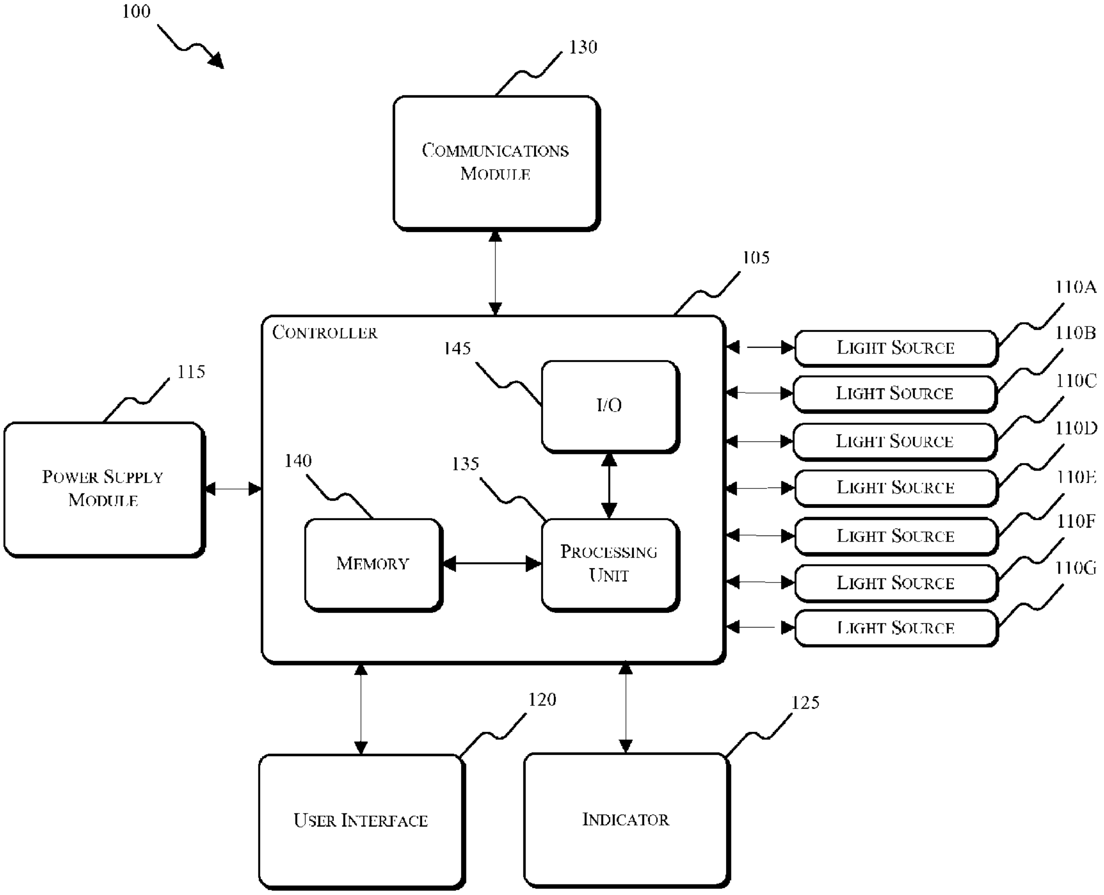

100
130
Communications Module
105
110A
Controller
145
I/O
110B
110C
110D
110E
110F
110G
Light Source
Light Source
Light Source
Light Source
Light Source
Light Source
Light Source
115
Power Supply Module
140
Memory
135
Processing Unit
120
User Interface
125
Indicator

FIG. 2

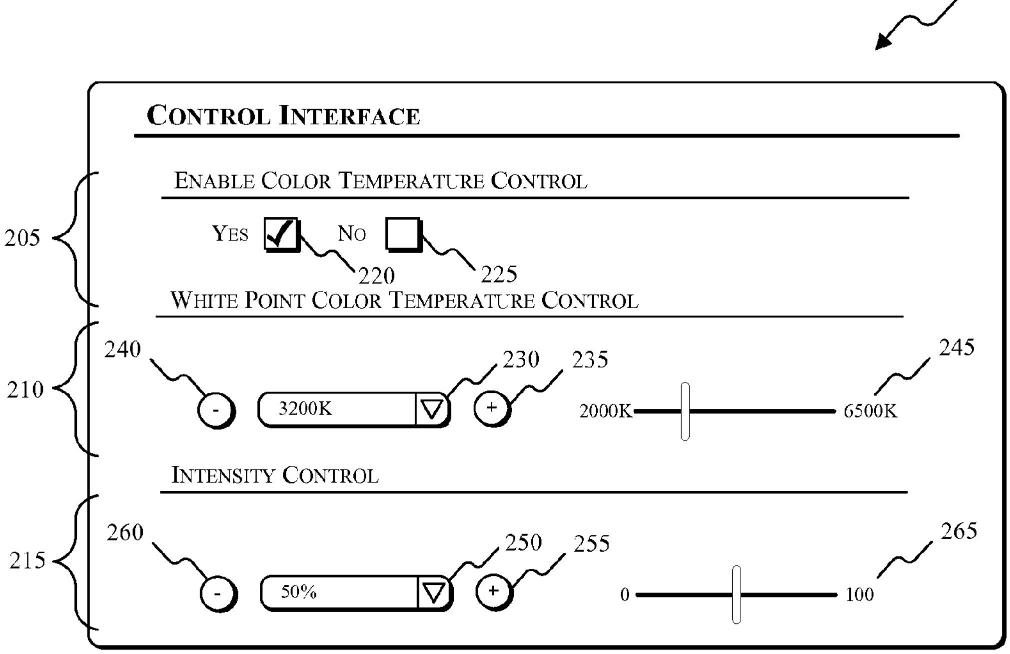

200
CONTROL INTERFACE
ENABLE COLOR TEMPERATURE CONTROL
YES ☑
NO ☐
220
225
205
WHITE POINT COLOR TEMPERATURE CONTROL
210
240
-
3200K
230
+
235
2000K
6500K
245
INTENSITY CONTROL
215
260
-
50%
250
+
255
0
100
265

FIG. 3

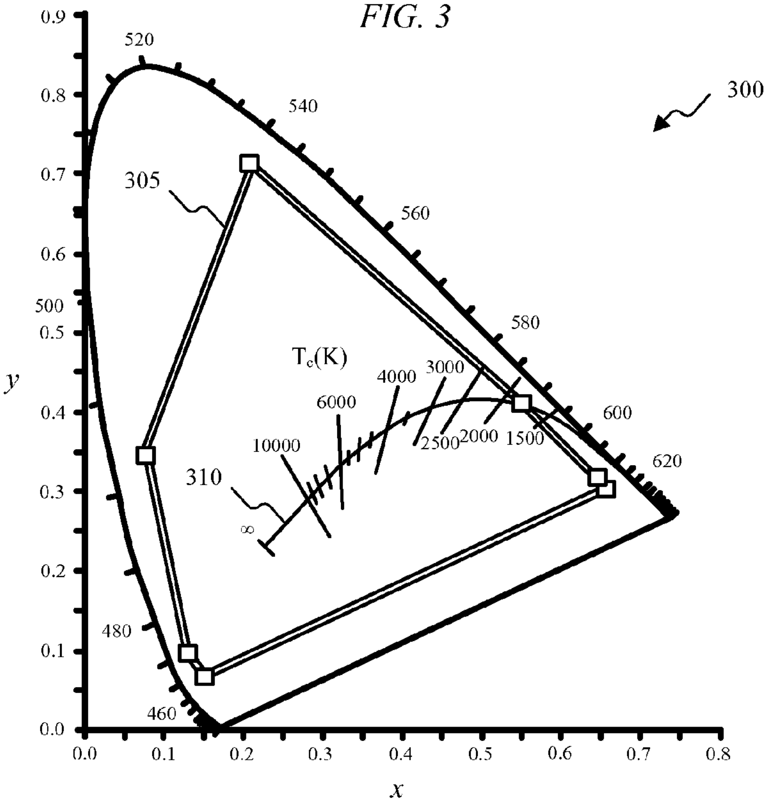
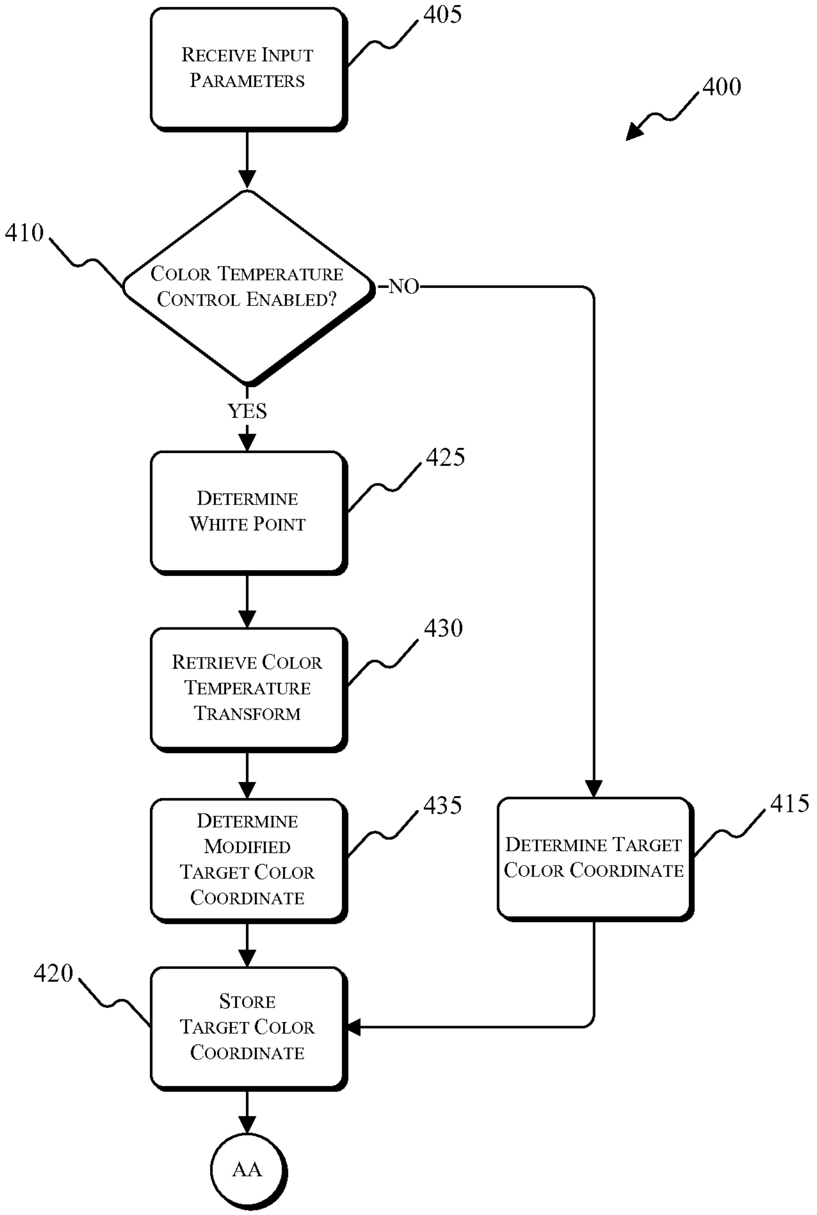

300
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
y
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
x
520
540
560
580
600
620
500
480
460
305
310
T_c(K)
4000
3000
6000
10000
2500
2000
1500
∞

FIG. 4



RECEIVE INPUT PARAMETERS
405
400
410
COLOR TEMPERATURE CONTROL ENABLED?
NO
YES
DETERMINE WHITE POINT
425
RETRIEVE COLOR TEMPERATURE TRANSFORM
430
DETERMINE MODIFIED TARGET COLOR COORDINATE
435
DETERMINE TARGET COLOR COORDINATE
415
420
STORE TARGET COLOR COORDINATE
AA

FIG. 5

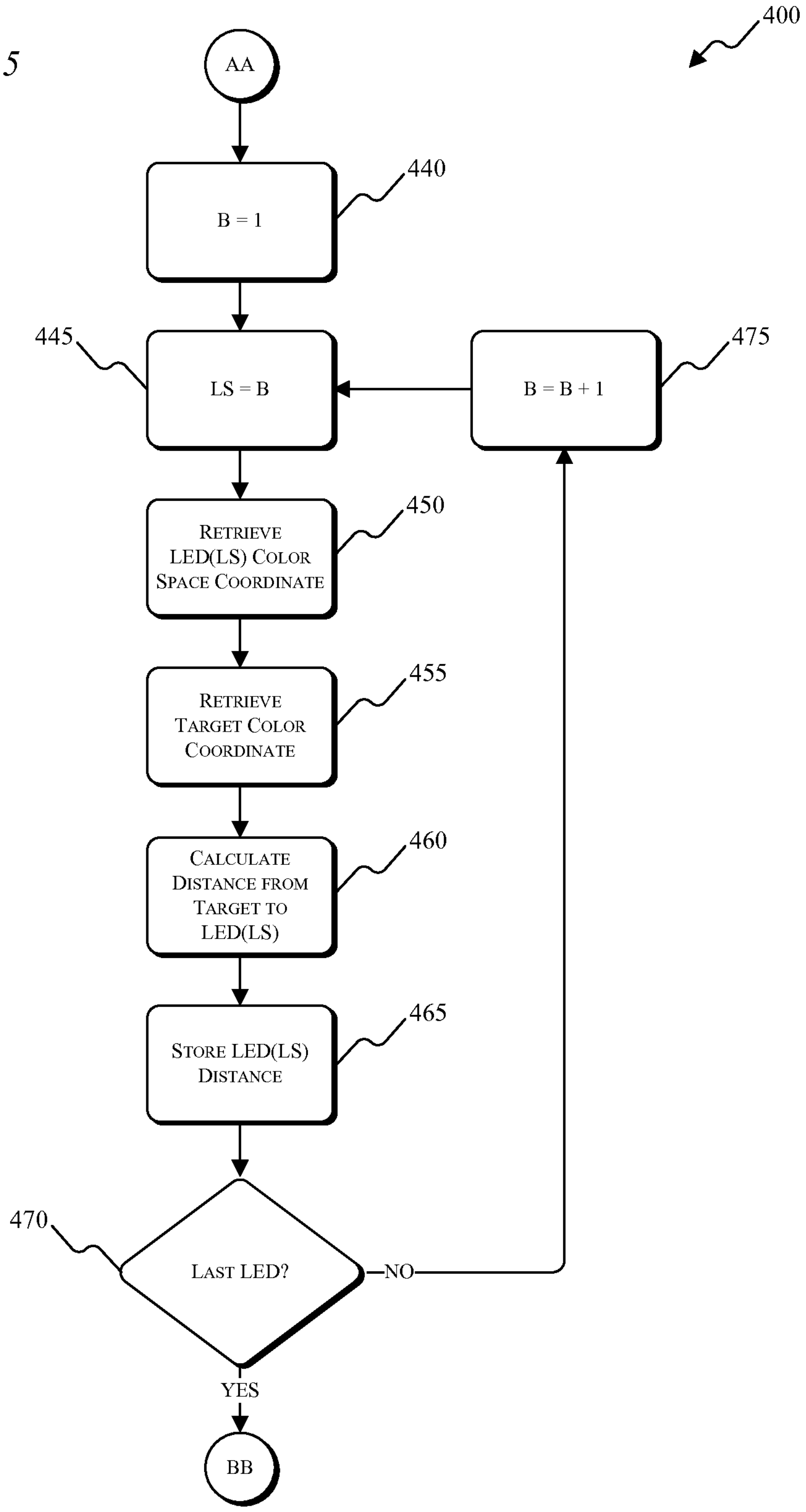

400
AA
B = 1
440
LS = B
445
B = B + 1
475
RETRIEVE LED(LS) COLOR SPACE COORDINATE
450
RETRIEVE TARGET COLOR COORDINATE
455
CALCULATE DISTANCE FROM TARGET TO LED(LS)
460
STORE LED(LS) DISTANCE
465
LAST LED?
470
NO
YES
BB

FIG. 6

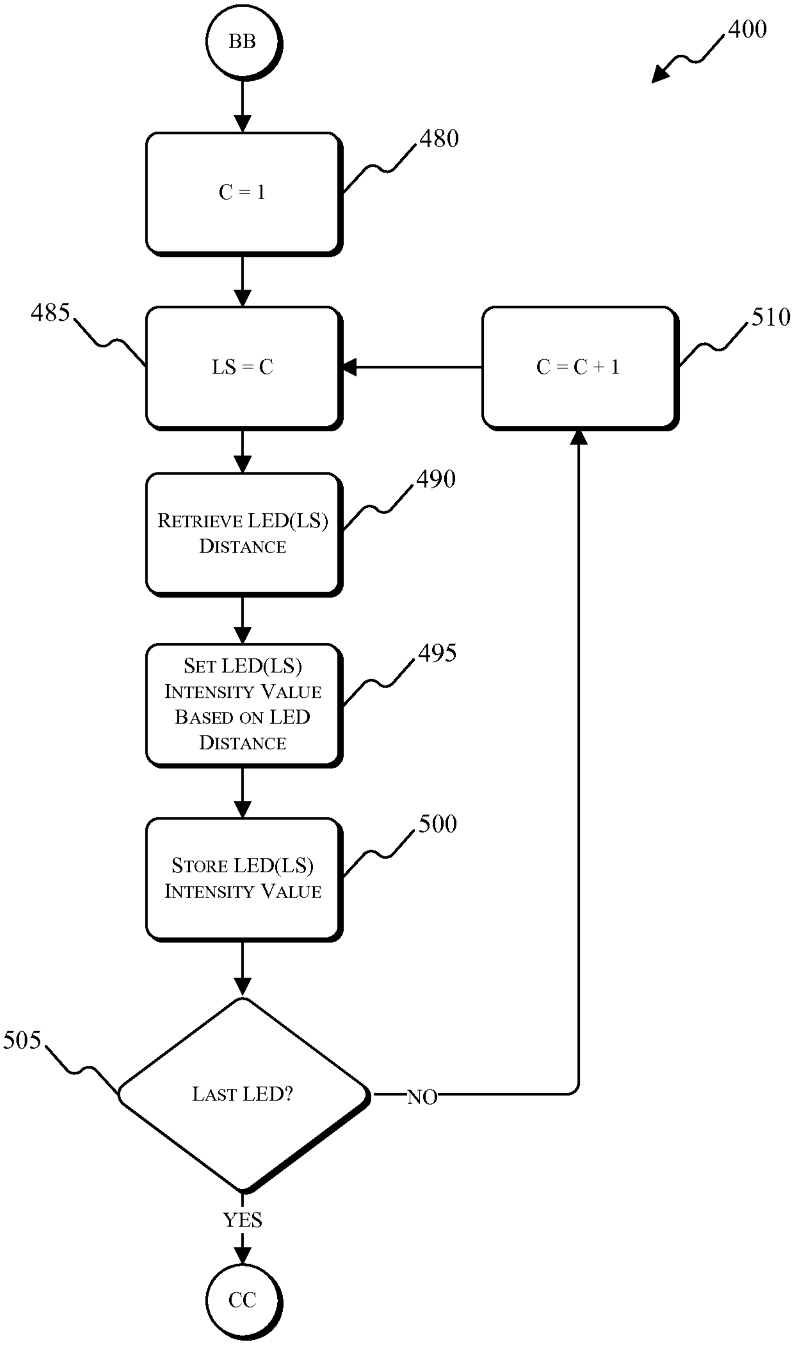

400
BB
C = 1
480
485
LS = C
C = C + 1
510
RETRIEVE LED(LS) DISTANCE
490
SET LED(LS) INTENSITY VALUE BASED ON LED DISTANCE
495
STORE LED(LS) INTENSITY VALUE
500
505
LAST LED?
NO
YES
CC

FIG. 7

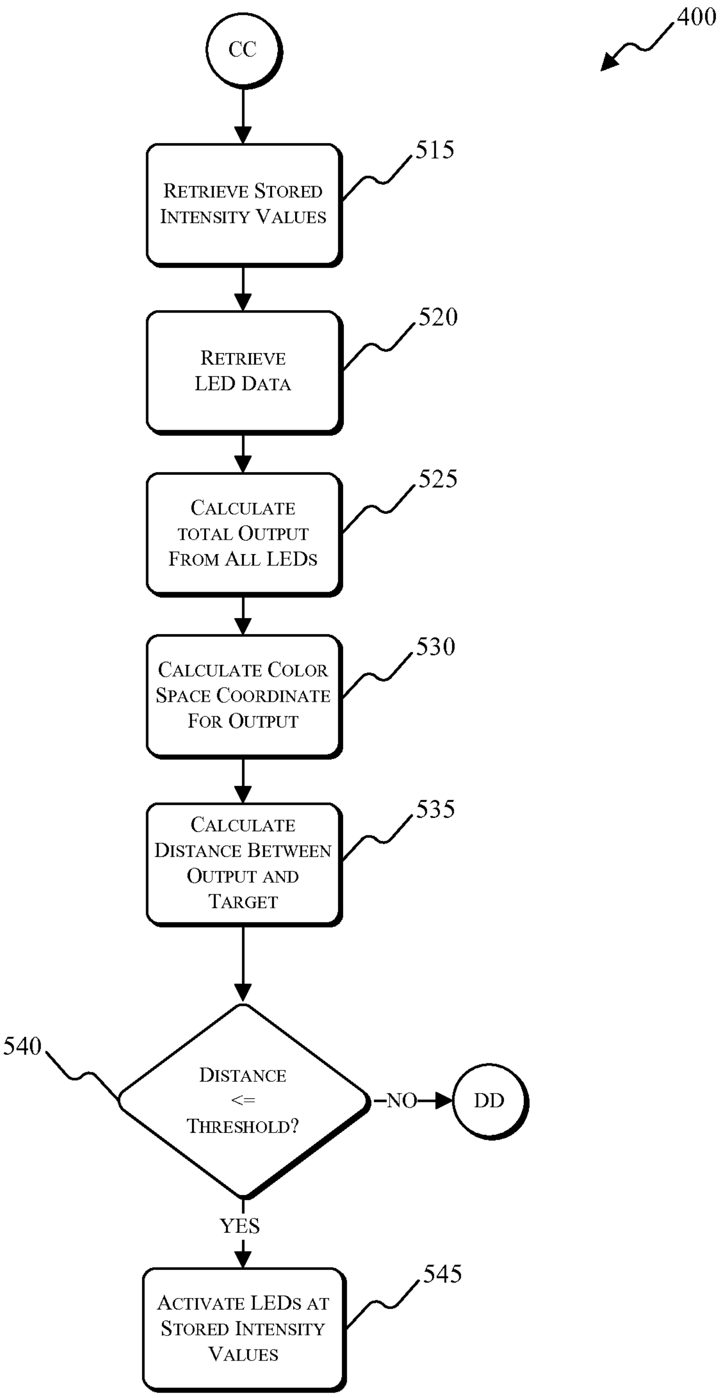

400
CC
515
RETRIEVE STORED INTENSITY VALUES
520
RETRIEVE LED DATA
525
CALCULATE TOTAL OUTPUT FROM ALL LEDS
530
CALCULATE COLOR SPACE COORDINATE FOR OUTPUT
535
CALCULATE DISTANCE BETWEEN OUTPUT AND TARGET
540
DISTANCE <= THRESHOLD?
NO
DD
YES
545
ACTIVATE LEDS AT STORED INTENSITY VALUES

FIG. 8

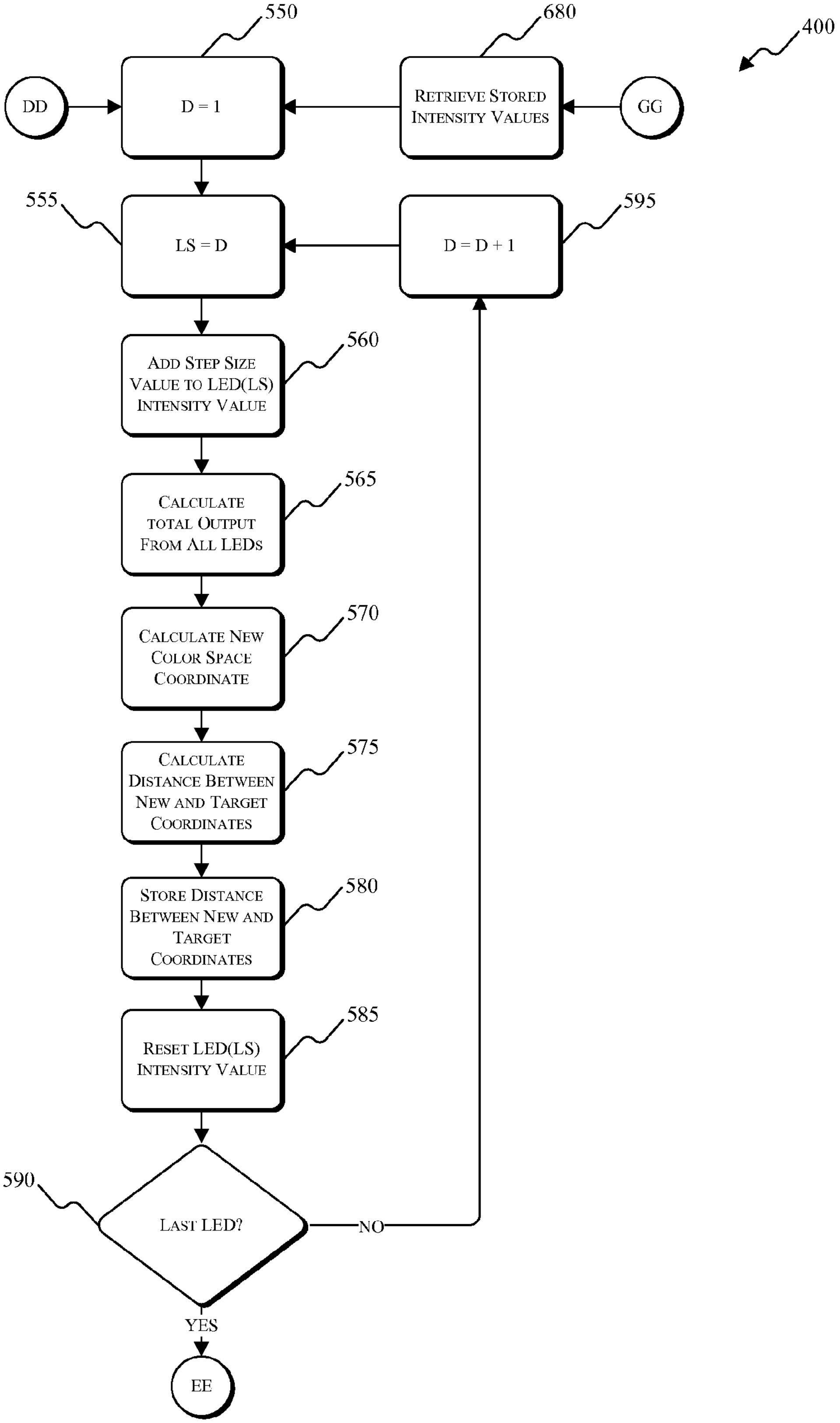

550
680
400
DD
D = 1
RETRIEVE STORED INTENSITY VALUES
GG
555
LS = D
D = D + 1
595
ADD STEP SIZE VALUE TO LED(LS) INTENSITY VALUE
560
CALCULATE TOTAL OUTPUT FROM ALL LEDS
565
CALCULATE NEW COLOR SPACE COORDINATE
570
CALCULATE DISTANCE BETWEEN NEW AND TARGET COORDINATES
575
STORE DISTANCE BETWEEN NEW AND TARGET COORDINATES
580
RESET LED(LS) INTENSITY VALUE
585
590
LAST LED?
NO
YES
EE

FIG. 9

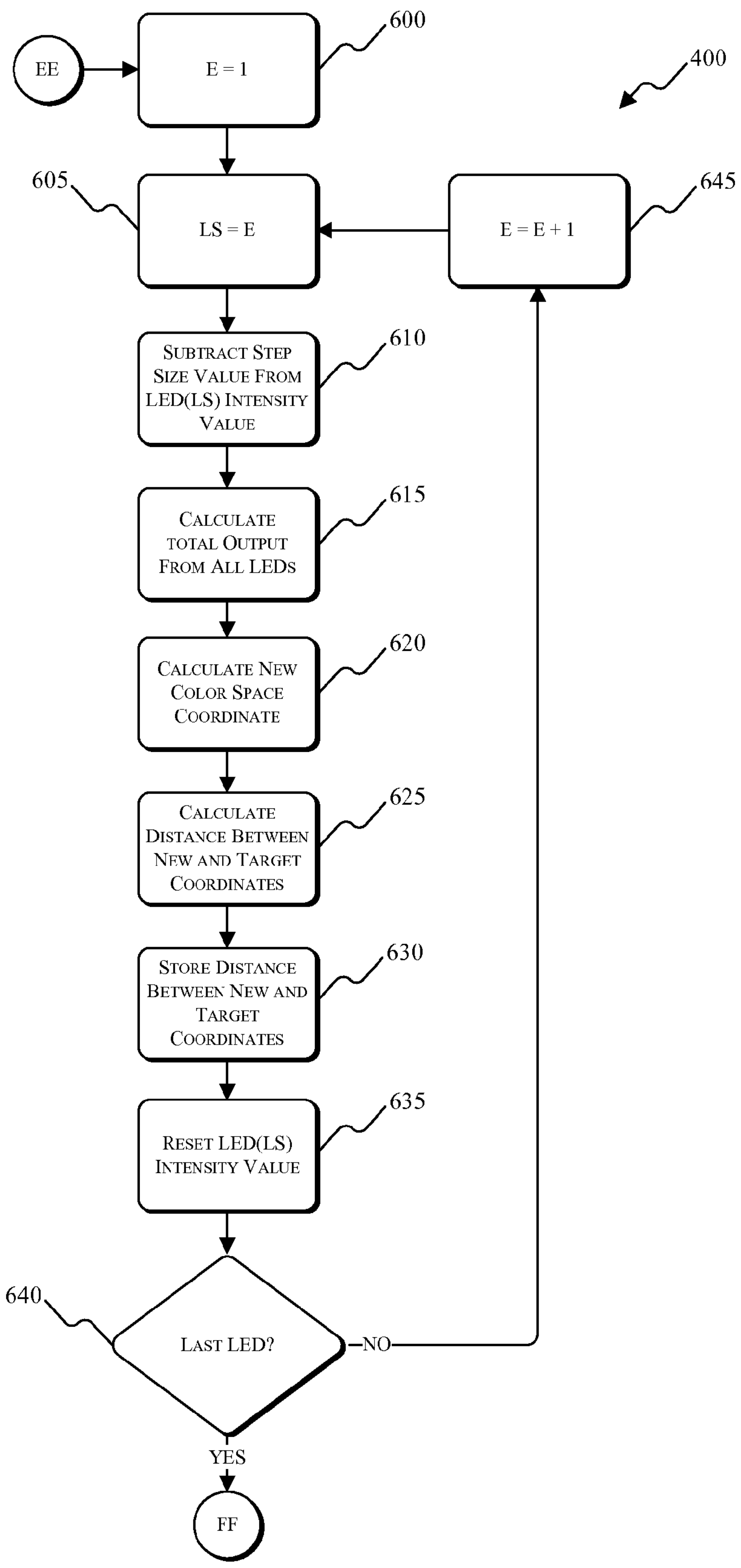
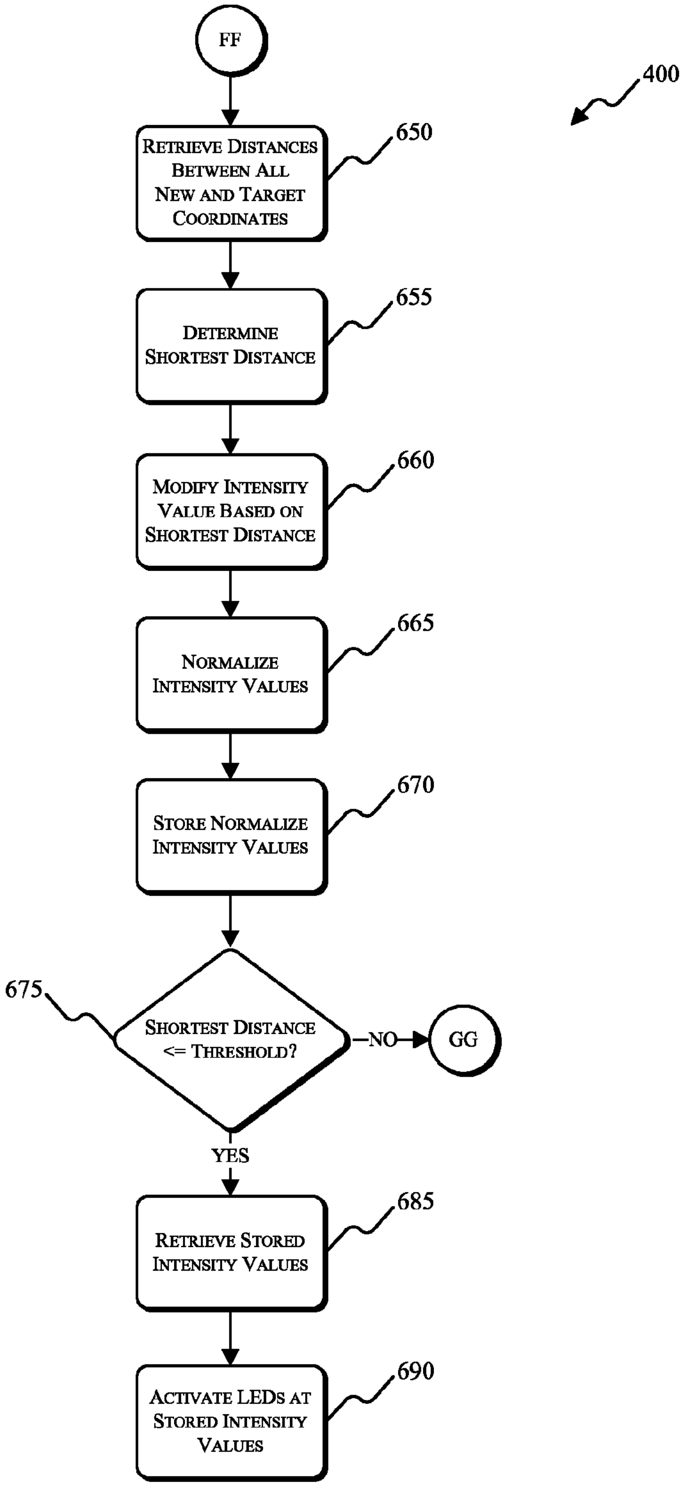

EE
E = 1
600
400
605
LS = E
E = E + 1
645
SUBTRACT STEP SIZE VALUE FROM LED(LS) INTENSITY VALUE
610
CALCULATE TOTAL OUTPUT FROM ALL LEDS
615
CALCULATE NEW COLOR SPACE COORDINATE
620
CALCULATE DISTANCE BETWEEN NEW AND TARGET COORDINATES
625
STORE DISTANCE BETWEEN NEW AND TARGET COORDINATES
630
RESET LED(LS) INTENSITY VALUE
635
640
LAST LED?
NO
YES
FF

FIG. 10


FF
400
RETRIEVE DISTANCES BETWEEN ALL NEW AND TARGET COORDINATES
650
DETERMINE SHORTEST DISTANCE
655
MODIFY INTENSITY VALUE BASED ON SHORTEST DISTANCE
660
NORMALIZE INTENSITY VALUES
665
STORE NORMALIZE INTENSITY VALUES
670
675
SHORTEST DISTANCE <= THRESHOLD?
NO
GG
YES
RETRIEVE STORED INTENSITY VALUES
685
ACTIVATE LEDS AT STORED INTENSITY VALUES
690

SYSTEMS AND METHODS FOR CONTROLLING AN OUTPUT OF A LIGHT FIXTURE

BACKGROUND

This invention relates to controlling an output of a light fixture.

The color temperature of a white-light light source (e.g., an incandescent light bulb) corresponds to the temperature of an ideal black-body radiator that radiates light of a comparable hue, and is identified in units of absolute temperature, Kelvin ("K"). Color temperatures of approximately 5,000K or greater are referred to as cool colors, and color temperatures between approximately 2,700K and 3,000K are referred to as warm colors. For example, the light output by an incandescent light bulb is thermal radiation and approximates an ideal black-body radiator. The color temperatures associated with the incandescent light bulb follow the Planckian locus through a particular color space (e.g., the CIE xyY color space) from low color temperatures (i.e., warm colors) to high color temperatures (i.e., cool colors). Accordingly, color temperature is a convenient way to describe the output of an incandescent light bulb or other similar white-light light sources.

SUMMARY

Although color temperature is convenient for describing the output of white-light light sources, color temperature is undefined with respect to light sources that do not approximate, or cannot be correlated to, ideal black-body radiators (e.g., red light emitting diodes ("LEDs"), green LEDs, blue LEDs, etc.). Such light sources cannot be individually described with respect to a color temperature. Although systems have been developed that use discrete color light sources (e.g., LEDs) to approximate white-light light sources, such systems are unable to produce a non-white output that mimics the color temperature changes of an ideal black-body radiator.

As such, the invention provides systems and methods for controlling an output of a light fixture. The light fixture includes four or more light sources. The light fixture, or a controller connected to the light fixture, is configured to produce an output that mimics the color temperature changes of an ideal black-body radiator based on a desired target color, a white point color temperature setting, and an intensity value. For example, input parameters corresponding to the desired target color and the intensity for the desired target color are inputted using a color control methodology (e.g., HSI, RGB, etc.). The white point color temperature setting is then determined based on the intensity value and a relationship between the intensity value and the color temperature of an ideal black-body radiator. A color temperature transform is then determined, selected, or identified based on the white point color temperature setting. The color temperature transform and the desired target color are used to determine a modified target color point within a color space (e.g., the CIE xyY color space). A set of light source output intensity values corresponding to the modified target color point are then identified, and the light sources are driven to the identified output intensity values.

In one implementation, the invention provides a method of controlling an output of a light fixture. The light fixture includes four or more light sources. The method includes receiving a first input parameter corresponding to a first color point within a color space, receiving a second input parameter associated with a desired intensity for the first color point, and determining a white point based on a relationship between the second input parameter and the color temperature of a black-body radiator. The white point corresponds to a second color point within the color space, and a color temperature transform is selected based on the white point. The method also includes calculating a third color point within the color space based on the color temperature transform, determining a respective light source output value for each of the four or more light sources based on the third color point, and driving each of the four or more light sources at the respective light source output value to produce the output of the light fixture. The color temperature transform defines a relationship between the first color point and the third color point. The third color point is different than the first color point, and the third color point is different than the second color point.

In another implementation, the invention provides a method of controlling an output of a light fixture. The light fixture includes four or more light sources. The method includes receiving a set of input parameters. The set of input parameters correspond to a first color point within a color space and an intensity for the first color point. The method also includes determining a color temperature setting based on a relationship between the set of input parameters and the color temperature of a black-body radiator. The color temperature setting corresponds to a second color point within the color space. A color temperature transform is determined based on the color temperature setting, and a third color point within the color space is calculated based on the color temperature transform. The color temperature transform defines a relationship between the first color point and the third color point. The third color point is different than the first color point, and the third color point is different than the second color point. The method also includes determining a respective light source output value for each of the four or more light sources based on the third color point, and driving each of the four or more light sources at the respective light source output value to produce the output of the light fixture.

In one construction, the invention provides a system for controlling the output of a light fixture. The system includes four or more light sources and a controller. The controller is configured to receive a first input parameter corresponding to a first color point within a color space, receive a second input parameter associated with a desired intensity for the first color point, and determine a white point based on a relationship between the second input parameter and the color temperature of a black-body radiator. The white point corresponds to a second color point within the color space, and a color temperature transform is selected based on the white point. The controller is also configured to calculate a third color point within the color space based on the color temperature transform, determine a respective light source output value for each of the four or more light sources based on the third color point, and drive each of the four or more light sources at the respective light source output value to produce the output of the light fixture. The color temperature transform defines a relationship between the first color point and the third color point. The third color point is different than the first color point, and the third color point is different than the second color point.

Other aspects of the invention will become apparent by consideration of the detailed description and accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a block diagram of a light fixture.

FIG. **2** is a control interface according to an embodiment of the invention.

FIG. **3** is the International Commission on Illumination ("CIE") 1931 color space chromaticity diagram and illustrates a gamut of a light fixture.

FIGS. **4-10** are a process for controlling an output of a light fixture.

DETAILED DESCRIPTION

Before any embodiments of the invention are explained in detail, it is to be understood that the invention is not limited in its application to the details of construction and the arrangement of components set forth in the following description or illustrated in the following drawings. The invention is capable of other embodiments and of being practiced or of being carried out in various ways.

The invention described herein relates to systems and methods for controlling an output of a light fixture. The light fixture includes four or more light sources. The light fixture, or a controller connected to the light fixture, is configured to produce an output that mimics the color temperature changes of an ideal black-body radiator based on one or more input parameters (e.g., a desired target color, a white point color temperature setting, an intensity value, etc.). For example, the input parameters corresponding to a desired target color and an intensity value for the desired color are inputted using one or more color control methodologies (e.g., HSI, RGB, etc.). The desired target color corresponds to a first color point or coordinate within a color space (e.g., the CIE xyY color space), and the intensity value corresponds to an intensity for the first color point. The white point color temperature setting is then determined, selected, or calculated based on, for example, the intensity value and a relationship between the intensity value and the color temperature of an ideal black-body radiator. The white point color temperature setting corresponds to a second color point or coordinate within the color space and is used to determine, select, or identify a color temperature transform. The color temperature transform defines a relationship between the first color point and a third color point or coordinate. The color temperature transform is then used to determine the third color point within the color space. The third color point is different from the first color point and the second color point. A set of light source output intensity values corresponding to the third color point are then identified, and the light sources are driven to the identified output intensity values.

In some implementations, light fixtures are used in, for example, a theatre, a hall, an auditorium, a studio, or the like. Each light fixture **100** includes, among other things, a controller **105**, a plurality of light sources **110A-110G**, a power supply module **115**, a user interface **120**, one or more indicators **125**, and a communications module **130**, as shown in FIG. **1**. In the illustrated construction, the light fixture **100** includes seven light sources **110A-110G**. Each light source is configured to generate light at a specific wavelength or range of wavelengths. For example, the light sources **110A-110G** generate light corresponding to the colors red, red-orange, amber, green, cyan, blue, and indigo. In other constructions, light sources that generate different colors are used (e.g., violet, yellow, etc.).

The controller **105** includes, or is connected to an external device (e.g., a computer), which includes combinations of software and hardware that are operable to, among other things, control the operation of one or more of the light fixtures, control the output of each of the light sources **110A-110G**, and activate the one or more indicators **125** (e.g., LEDs or a liquid crystal display ("LCD")). In one construction, the controller **105** or external device includes a printed circuit board ("PCB") (not shown) that is populated with a plurality of electrical and electronic components that provide power, operational control, and protection to the light fixtures. In some constructions, the PCB includes, for example, a processing unit **135** (e.g., a microprocessor, a microcontroller, or another suitable programmable device), a memory **140**, and a bus. The bus connects various components of the PCB including the memory **140** to the processing unit **135**. The memory **140** includes, for example, a read-only memory ("ROM"), a random access memory ("RAM"), an electrically erasable programmable read-only memory ("EEPROM"), a flash memory, a hard disk, or another suitable magnetic, optical, physical, or electronic memory device. The processing unit **135** is connected to the memory **140** and executes software that is capable of being stored in the RAM (e.g., during execution), the ROM (e.g., on a generally permanent basis), or another non-transitory computer readable medium such as another memory or a disc. Additionally or alternatively, the memory **140** is included in the processing unit **135**. The controller **105** also includes an input/output ("I/O") system **145** that includes routines for transferring information between components within the controller **105** and other components of the light fixtures or system. For example, the communications module **130** is configured to provide communication between the light fixture **100** and one or more additional light fixtures or another control device within a lighting system.

Software included in the implementation of the light fixture **100** is stored in the memory **140** of the controller **105**. The software includes, for example, firmware, one or more applications, program data, one or more program modules, and other executable instructions. The controller **105** is configured to retrieve from memory and execute, among other things, instructions related to the control processes and methods described below. For example, the controller **105** is configured to execute instructions retrieved from the memory **140** for performing a mathematical transformation of a control value to a value that is required to drive the light sources **110A-110G** to produce a desired color. In other constructions, the controller **105** or external device includes additional, fewer, or different components.

The PCB also includes, among other things, a plurality of additional passive and active components such as resistors, capacitors, inductors, integrated circuits, and amplifiers. These components are arranged and connected to provide a plurality of electrical functions to the PCB including, among other things, filtering, signal conditioning, or voltage regulation. For descriptive purposes, the PCB and the electrical components populated on the PCB are collectively referred to as the controller **105**.

The user interface **120** is included to control the light fixture **100** or the operation of a lighting system as a whole. The user interface **120** is operably coupled to the controller **105** to control, for example, the output of the light sources **110A-110G**. The user interface **120** can include any combination of digital and analog input devices required to achieve a desired level of control for the system. For example, the user interface **120** can include a computer having a display and input devices, a touch-screen display, a plurality of knobs, dials, switches, buttons, faders, or the like. In some constructions, the user interface is separated from the light fixture **100**.

The power supply module **115** supplies a nominal AC or DC voltage to the light fixture **100** or system of light fixtures. The power supply module **115** is powered by mains power having nominal line voltages between, for example, 100V and 240V AC and frequencies of approximately 50-60 Hz. The power supply module **115** is also configured to supply lower voltages to operate circuits and components within the light fixture **100**. In other constructions, the light fixture **100** is powered by one or more batteries or battery packs.

As illustrated in FIG. **1**, the controller **105** is connected to light sources **110**A-**110**G. In other constructions, the controller **105** is connected to, for example, red, green, and blue ("RGB") light sources, red, green, blue, and amber ("RGBA") light sources, red, green, blue, and white ("RGBW") light sources, or other combinations of light sources. A seven light source implementation is illustrated because it is operable to reproduce substantially the entire spectrum of visible light. In other implementations, eight or more light sources are used to further enhance the light fixtures ability to reproduce visible light.

FIG. **2** illustrates a control interface **200** for controlling the color temperature of the output of the light fixture **100**. In some constructions, the control interface **200** is included in the user interface **120**. The control interface **200** is, for example, a graphical user interface ("GUI") that is displayed on a monitor or a similar display. In some constructions, the control interface **200** is a physical interface and includes one or more buttons, knobs, dials, faders, or the like. The illustrated control interface **200** includes an enable color temperature control section **205**, a white point color temperature control section **210**, and an intensity control section **215**. Although the intensity control section **215** is illustrated as being separate from, for example, target color controls (e.g., hue control, saturation control, individual light source control, etc.), the intensity control section **215** can alternatively be included with the target color controls. The enable color temperature control section **205** includes a YES checkbox **220** and a NO checkbox **225**. The checkboxes **220** and **225** are used to select or deselect automatic color temperature control. As described in greater detail below, the automatic color temperature control is configured to automatically modify a user selected target color to mimic the color temperature changes of an ideal black-body radiator. Once enabled, the color temperature control can use a white point setting from the white point color temperature control section **210** to modify a target color to produce an output of the light fixture that mimics the color temperature changes of a black-body radiator. Additionally or alternatively, an intensity setting from the intensity control section **215** can be used to modify a target color to produce an output of the light fixture that mimics the color temperature changes of a black-body radiator.

The white point color temperature control section **210** includes a white point input portion **230**, an increment button **235**, a decrement button **240**, and a fader **245**. The white point input portion **230** is controlled by directly selecting and modifying a white point setting for the output of the light fixture. For example, a user is able to modify or populate the white point input portion **230** with a desired white point color temperature (i.e., a value in Kelvin). The user populates the white point input portion **230** by entering text via a mechanical or virtual keyboard of a computer or similar processing device, and using a pointing or selection device such as a mouse to control a curser on the display. Input signals from the keyboard and the mouse are received, processed, and translated into a visual result or action in the interface **200**. For example, if the user enters text using a keyboard, the activated keys

produce signals which are represented as type-written text in the interface **200**. Similarly, a mouse click, which corresponds to a location of the cursor on the screen, results in selecting/deselecting the increment button **235**, the decrement button **240**, a dropdown menu, the position of the fader **245**, etc. In other implementations, the interface **200** is accessed and controlled using a touch-screen device and a user's finger strokes or tapping are used to populate or modify the white point input portion **230**.

Like the white point color temperature control section **210**, the intensity control section **215** includes an intensity input portion **250**, an increment button **255**, a decrement button **260**, and a fader **265**. The intensity input portion **250** is controlled by directly selecting and modifying an intensity setting or value for the target color. For example, a user is able to modify or populate the intensity input portion **250** with a desired intensity setting or value (e.g., a percent). The intensity input portion **250** is modified or populated in a manner similar to that described above with respect to the white point input portion **230**.

FIG. **3** illustrates the CIE xyY color space **300** and the available color gamut **305** for the light fixture **100**. As such, only colors that fall within or on the illustrated color gamut **305** are reproducible by the light fixture **100**. Also illustrated is the Planckian locus **310**, which illustrates the various color temperatures for an idea black-body radiator.

The CIE xyY color space **300** represents x-coordinates with values between 0.0 and 0.8, and y-coordinates with values between 0.0 and 0.9. To avoid floating point calculations, 16-bit integers are used in some constructions to represent both the x-coordinate and the y-coordinate. An integer value of zero corresponds to a coordinate of 0.0, and an integer value of 32,767 corresponds to a coordinate of 1.0. Therefore, some constructions of the invention achieve a resolution of $1/_{32,767}$ or approximately 0.00003.

The invention can be implemented using a variety of color control, targeting, and matching methodologies, such as HSI, RGB, CYM, YIQ, YUV, HSV, HLS, XYS, etc. The techniques described below are exemplary, and other techniques for controlling the output of the light fixture **100** to mimic the color temperature changes of an ideal black-body radiator are within the spirit and scope of the invention. Additionally, the invention is capable of being implemented internal to or external from the light fixture **100**. For example, the light fixture **100** can include sufficient memory and processing power to execute one or more programs associated with the inventive methods. Additionally or alternatively, a separate computer (e.g., a central computer, a control panel, a controller, etc.) includes sufficient memory and processing power to execute one or more programs associated with the inventive methods.

FIGS. **4-10** are a process **400** for controlling an output of a light fixture to mimic the color temperature changes of an ideal black-body radiator. The steps of the process **400** are described in an iterative manner for descriptive purposes. Various steps described herein with respect to the process **400** are capable of being executed simultaneously, in parallel, or in an order that differs from the illustrated serial and iterative manner of execution. A target color and various parameters associated with the target color, the output of the light fixture, settings of the light fixture, etc. are inputted as one or more input parameters (e.g., a set of input parameters) (step **405**) to the light fixture using a complex color control methodology (e.g., HSI, RGB, etc.). The target color corresponds to a target color point or coordinate within a color space, such as the CIE xyY color space. The input parameters are received from, for example, a controller or user interface (e.g., the user interface

120), which allows a user to enter a desired target color, a hue setting, a saturation setting, a white point setting, an intensity setting, individual light source settings, etc. Additionally or alternatively, the controller receives or retrieves a desired target color, a hue setting, a saturation setting, a white point setting, an intensity setting, individual light source settings, etc. from memory (e.g., as part of a program or sequence of desired colors and settings). In some implementations, the input parameters can be stored in either a volatile or non-volatile memory. For example, if one or more of the input parameters have already been stored to a non-volatile memory (e.g., a ROM), the stored one or more input parameters can be retrieved and stored in, for example, a RAM or similar memory used to store information necessary for the execution of the process **400**.

Following step **405**, light fixture **100** or a controller connected to the light fixture **100** determines whether color temperature control is enabled (step **410**). For example, the color temperature control can be enabled using the control interface **200** described above with respect to FIG. **2**. In some implementations, selecting the YES checkbox **220** in FIG. **2** causes an indicator (e.g., a flag, a bit, etc.) to be set. In such implementations, a flag or a bit set to a value of "1" can indicate that the color temperature control is enabled. In other implementations, setting the YES checkbox **220** sets a software pointer to a desired program associated with color temperature control. For example, if the NO checkbox **225** in FIG. **2** is selected, the pointer points to, or causes to be accessed, a software program that does not include executable instructions for controlling the output of the light fixture to mimic color temperature changes. If the YES checkbox **220** is selected, the pointer points to, or causes to be accessed, a software program that includes executable instructions associated with the control of the output of the light fixture to mimic color temperature changes.

If, at step **410**, the color temperature control is not enabled, the input parameters are used to determine a target color point or coordinate (step **415**) within a color space (e.g., the CIE xyY color space) using, for example, a standard color space conversion (e.g., based on tristimulus values). The target color coordinate substantially corresponds to the desired target color. The tristimulus values correspond to the amounts of three primary colors in a three-component additive color model that are needed to match a target color. The tristimulus values, denoted by X, Y, and Z, are derived parameters that are used to represent the human eye's response to red, green, and blue colors and are calculated using three corresponding color matching functions. The target color coordinate is determined based on the calculated tristimulus values and includes an x-coordinate and a y-coordinate which correspond to a location within the color space (see FIG. **3**). The target color coordinate is then stored in memory (step **420**).

If the color temperature control is enabled at step **410**, a white point color temperature setting for the output of the light fixture is determined (step **425**). The white point color temperature setting corresponds to a white point color coordinate within the color space that substantially lies on the Planckian locus. In some implementations, the white point color coordinate is different from the target color coordinate (e.g., the target color coordinate does not substantially lie on the Planckian locus). In other implementations, the white point color coordinate is the same as the target color coordinate. As described above, the control interface **200** can be used to set or select a white point color temperature or an intensity value. Additionally or alternatively, a predetermined or preselected white point color temperature setting (e.g., a default white point color temperature setting) can be retrieved from memory. In some implementations, the intensity value is used to determine the white point color temperature setting. For example, depending on the intensity value, one of a plurality of calculated or predetermined white point color temperatures is selected. In other implementations, a white point color temperature is selected using the control interface **200**, and the intensity value is used to scale the selected white point color temperature. For example, the selected white point color temperature can be set as a maximum white point color temperature. As the intensity value is decreased, the user-selected white point color temperature is decreased. Additional selection techniques can also be used. For example, the user-selected white point color temperature may correspond to 50% intensity. In such an implementation, as the intensity value is increased, the white point color temperature is increased, and as the intensity value is decreased, the white point color temperature is decreased.

In some implementations, the white point color temperature setting is set using the intensity input portion **250** described above with respect to FIG. **2**. For example, the intensity input portion **250** and the control interface **200** are used to generate a signal corresponding to a desired intensity value (i.e., an input parameter) that is received by a controller (e.g., the controller **105**). The desired intensity value is correlated to a color temperature based on one or more relationships (e.g., estimations, interpolations, extrapolations, regressions, least squares approximations, linear approximations, non-linear approximations, Taylor series, power series, etc.). As an illustrative example of a relationship between an intensity value and a color temperature, the desired intensity value is converted to a desired intensity value in lumens. An exemplary conversion is provided below in EQN. 1.

$$\text{Lumens} = \text{Max Lumens} \times \left(\frac{\text{Actual Intensity}}{\text{Max Intensity}}\right)^X \qquad \text{EQN. 1}$$

where the maximum intensity is the maximum intensity setting for the light fixture (e.g., 255 for an 8-bit input value), the actual intensity is the intensity value setting based on the input parameter, the maximum lumens is the maximum lumen setting for the light fixture, and the exponent, X, has a value that is based on a manner in which the intensity of the light fixture is dimmed.

The desired intensity value in lumens can then be correlated to an intensity value in volts. An exemplary conversion is provided below in EQN. 2.

$$\text{Volts} = \text{Max Volts} \times \left(\frac{\text{Actual Lumens}}{\text{Max Lumens}}\right)^Y \qquad \text{EQN. 2}$$

where the maximum volts is the maximum volt reading for the light fixture, the maximum lumens is the maximum lumen setting for the light fixture (e.g., 255 for an 8-bit input value), the actual lumens is the lumen setting calculated using EQN. 1, and the exponent, Y, has a value that is based on a relationship between lumens and volts for the light fixture **100**.

The intensity value in volts is then converted to a color temperature. An exemplary conversion is provided below in EQN. 3.

$$\text{Color Temperature} = \text{Max Color } Temp \times \left(\frac{\text{Actual Volts}}{\text{Max Volts}}\right)^Z \quad \text{EQN. 3}$$

where the maximum color temperature is a maximum color temperature setting for the light fixture or the maximum color temperature achievable by the light fixture. The maximum volts is the maximum volt reading for the light fixture, the actual volts is the volt setting calculated using EQN. 2, and the exponent, Z, has a value that is based a relationship between color temperature and volts for the light fixture **100**. The calculated color temperature can then be associated with, or approximated to, a color space coordinate (e.g., an x-y coordinate at (x_w, y_w)) that lies on the Planckian locus and corresponds to the color temperature of an ideal black-body radiator. Each of the conversions shown in EQNS. 1-3 can be combined into a single conversion or relationship, or can be executed separately. The relationships between the intensity values and color temperature are then used to generate one or more color temperature transforms, as described below. In some implementations, the relationships between each of the intensity values and a color temperature are stored in memory. Additionally or alternatively, the color temperatures corresponding to particular intensity values are stored in memory. For example, depending on a desired resolution for the color temperature control, a predetermined number of color temperature values are stored in memory (e.g., 256 values, 65,536 values, etc.) that correspond to discrete intensity values or ranges of intensity values.

Returning to the process **400**, a color temperature transform is then selected and retrieved (i.e., from memory) based on the white point color temperature (step **430**), and the input parameters are used to determine a modified target color coordinate based on the color temperature transform (step **435**). In some implementations, the modified target color coordinate is different from the target color coordinate and the white point color coordinate (e.g., the modified target color coordinate does not substantially lie on the Planckian locus). In other implementations, the modified target color coordinate is the same as the white point color coordinate.

The color temperature transform is configured to generate a modified target color coordinate based on the desired target color. The color temperature transform is different than the standard color space conversion described above. As an illustrative example, given a particular target color, the standard color space conversion and the color temperature transform each generate a different color space coordinate. The color space coordinate generated using the known color space conversion substantially corresponds to the target color. However, the color space coordinate generated or determined using the color temperature transform is shifted within the color space in order to mimic the color temperature changes of an ideal black-body radiator.

The color temperature transforms are generated based on a selected color gamut (e.g., the RGB color gamut) that can be defined with respect to the CIE xyY color space **300**. For example, as described above, the user is able to select a desired target color based on any of a number of complex color control methodologies. The input values from the complex color control methodology are then associated with the RGB color gamut (e.g., R_T, G_T, B_T), which is represented by a triangle in the CIE xyY color space having a red coordinate (x_R, y_R), a green coordinate (x_G, y_G), and a blue coordinate (x_B, y_B), which have predetermined values. The red coordinate, the green coordinate, and the blue coordinate correspond to the bounds of the RGB color gamut. The red coordinate, the green coordinate, and the blue coordinate are used to generate tristimulus values associated with each coordinate, as well as generate the color temperature transforms. For example, the tristimulus values for the red coordinate can be calculated using EQNS. 4-6 below.

$$X_R = \frac{x_R}{y_R} \quad \text{EQN. 4}$$

$$Y_R = 1 \quad \text{EQN. 5}$$

$$Z_R = \frac{(1 - x_R - y_R)}{y_R} \quad \text{EQN. 6}$$

In a similar manner, the tristimulus values for the green coordinate can be calculated using EQNS. 7-9 below.

$$X_G = \frac{x_G}{y_G} \quad \text{EQN. 7}$$

$$Y_G = 1 \quad \text{EQN. 8}$$

$$Z_G = \frac{(1 - x_G - y_G)}{y_G} \quad \text{EQN. 9}$$

The tristimulus values for the blue coordinate can be calculated using EQNS. 10-12 below.

$$X_B = \frac{x_B}{y_B} \quad \text{EQN. 10}$$

$$Y_B = 1 \quad \text{EQN. 11}$$

$$Z_B = \frac{(1 - x_B - y_B)}{y_B} \quad \text{EQN. 12}$$

In some implementations, the tristimulus values for the red coordinate, the green coordinate, and the blue coordinate are calculated once and stored in memory. In other implementations, the tristimulus values are calculated continually, at predetermined intervals, or based on a user input.

After the white point color temperature and corresponding color space coordinate for the white point color temperature have been determined, as described above, tristimulus values for the white point color temperature can also be determined. For example, the tristimulus values for the white point color temperature can be calculated using EQNS. 13-15 below.

$$X_W = \frac{x_W}{y_W} \quad \text{EQN. 13}$$

$$Y_W = 1 \quad \text{EQN. 14}$$

$$Z_W = \frac{(1 - x_W - y_W)}{y_W} \quad \text{EQN. 15}$$

Using the tristimulus values for the red coordinate, the green coordinate, the blue coordinate, and the white point coordinate, a matrix of scale factors, S, can be calculated, as shown below in EQN. 16.

$$\begin{bmatrix} S_R \\ S_G \\ S_B \end{bmatrix} = \begin{bmatrix} X_R & X_G & X_B \\ Y_R & Y_G & Y_B \\ Z_R & Z_G & Z_B \end{bmatrix}^{-1} \begin{bmatrix} X_W \\ Y_W \\ Z_W \end{bmatrix} \qquad \text{EQN. 16}$$

The matrix of scale factors, S, can then be used to calculate the tristimulus values associated with a modified target color, as shown below in EQN. 17.

$$\begin{bmatrix} X_W \\ Y_W \\ Z_W \end{bmatrix} = \begin{bmatrix} S_R X_R & S_G X_G & S_B X_B \\ S_R Y_R & S_G Y_G & S_B Y_B \\ S_R Z_R & S_G Z_G & S_B Z_B \end{bmatrix} \begin{bmatrix} R_T \\ G_T \\ B_T \end{bmatrix} \qquad \text{EQN. 17}$$

where R_T, G_T, and B_T are red, green, and blue values corresponding to the desired target color.

The x-y color coordinate (i.e., chromaticity) of the modified target color is then determined as a function of the tristimulus values X_M, Y_M, and Z_M, as shown below in EQNS. 18-20.

$$x_M = \frac{X_M}{(X_M + Y_M + Z_M)} \qquad \text{EQN. 18}$$

$$y_M = \frac{Y_M}{(X_M + Y_M + Z_M)} \qquad \text{EQN. 19}$$

$$z_M = \frac{Z_M}{(X_M + Y_M + Z_M)} = 1 - x_M - y_M \qquad \text{EQN. 20}$$

In some implementations, the relationships or transforms between the target color coordinate and the modified target color coordinate described above with respect EQNS. 1-20 are combined into a single relationship to, for example, reduce processing time, processing requirements, and memory usage. In other implementations, the color temperature transforms corresponding to particular intensity values are stored in memory. For example, depending on a desired resolution for the color temperature control, a predetermined number of color temperature transforms are stored in memory (e.g., 256 transforms, 65,536 transforms, etc.) that correspond to discrete intensity values or ranges of intensity values. A color temperature transform can then be determined or retrieved from memory based on the intensity setting or stored color temperature value, and the x-y coordinate of the modified target color is determined based on the target color and the color temperature transform.

As described above, the target color coordinate determined using the color temperature transform is different from the target color coordinate that is determined using the standard conversion. As such, the target color coordinate determined using the color temperature transform is indicated as a "modified" target color coordinate. For descriptive purposes, the target color coordinate and the modified target color coordinate are each referred to as the target color coordinate with respect to the remainder of the process **400** (i.e., starting at step **420**), because the remainder of the process **400** is substantially independent of the manner in which the target color coordinate was calculated. The target color coordinate is then stored to memory (step **420**) and the process **400** proceeds to section AA shown in and described with respect to FIG. **5**.

With reference to FIG. **5**, a second variable, B, is initialized or set equal to one (step **440**), and the light source variable, LS, is set equal to B (e.g., the first light source) (step **445**). The light fixture **100**, or a controller connected to the light fixture **100**, uses stored spectral information for each of the light sources within the light fixture **100** (e.g., output intensities of the light sources with respect to wavelength) to determine a location for each light source within a particular color space (e.g., the CIE xyY color space **300**). The spectral data for each of the light sources is sampled or gathered, for example, at the time of manufacture and stored in a memory. The spectral data is stored in a memory of the light fixture as a table or multiple tables of values. The values associated with the tables are accessed or retrieved to calculate an output of the light fixture (e.g., as a coordinate within a color space) without having to activate the light sources and use light sensors. The coordinates are also stored in memory, and can be accessed from memory for comparison to one or more additional calculated coordinates within a color space (e.g., the target color coordinate). In some implementations, the spectral data is gathered, stored, and utilized in a manner similar to that described in U.S. patent application Ser. No. 12/898,127, filed Oct. 5, 2010 and titled "SYSTEM AND METHOD FOR COLOR CREATION AND MATCHING," the entire content of which is hereby incorporated by reference.

At step **450**, the color space coordinate for the selected light source is retrieved from memory. The target color coordinate is also retrieved from memory (step **455**). The distance between the target color coordinate and the color space coordinate for the first light source is then calculated (step **460**). For example, if the target color coordinate is designated by an x-coordinate, x_T, and a y-coordinate, y_T, and the first light source is designated by an x-coordinate, x_1, and a y-coordinate, y_1, the distance, D_1, between the target color coordinate and the first light source coordinate can be calculated as shown below in EQN. 21. EQN. 21 can be used to calculate the distance between each of the light sources in the light fixture and the target color coordinate.

$$D_1 = \sqrt{(x_T - x_1)^2 + (y_T - y_1)^2} \qquad \text{EQN. 21}$$

The calculated distance, D_1, for the first light source is then stored in memory (step **465**). The selected light source corresponding to the second variable, B, is compared to the number of LEDs in the light fixture (step **470**). If the selected light source is not the last light source in the light fixture, the second variable, B, is incremented by one (step **475**) and the light source variable, LS, is reset to the new value of the second variable, B (step **445**). If the selected light source is the last light source in the light fixture, the process **400** proceeds to section BB shown in and described with respect to FIG. **6**.

The locations described herein generally relate to positions or coordinates within a color space that can be used to map colors in one, two, or three dimensional space, and allow for the consistent identification of colors. Implementations and constructions of the invention are described herein with respect to the CIE xyY color space, but other color spaces can also be used. The separations between the locations within the color space are described generally with respect to distances. However, the separations can also be based on, for example, ratios, products, sums, or differences between wavelengths, frequencies, intensities, polarizations, phases, color temperature, brightness, saturation, etc., and correspond generally to an intervening space or gap between points, values, quantities, objects, locations, and the like.

With reference to FIG. **6**, a third variable, C, is initialized or set equal to one (step **480**), and the light source variable, LS, is set equal to C (e.g., the first light source) (step **485**). At step **490**, the distance between the first light source and the target color coordinate is retrieved from memory. An intensity level for the first light source is then set based on the retrieved distance (step **495**), and the intensity level is stored to memory (step **500**). For example, the greater the distance between the light source color space coordinate and the target color coordinate, the lower the initial intensity value is set. As such, the distance between the light source color space coordinate, and the target color coordinate and the initial output intensity value for the light source are inversely related. In some implementations, the inverse relationship is a linear inverse relationship. In other implementations, the inverse relationship is an exponential, logarithmic, or the like. The light source intensities are, for example, one byte. Therefore, each light source intensity has a value between 0 (i.e., no output) and 255 (i.e., full-scale). After the initial output intensity value for light source is set, the selected light source corresponding to the third variable, C, is compared to the number of LEDs in the light fixture (step **505**). If the selected light source is not the last light source in the light fixture, the third variable, C, is incremented by one (step **510**) and the light source variable, LS, is reset to the new value of the third variable, C (step **485**). If the selected light source is the last light source in the light fixture, the process **400** proceeds to section CC shown in and described with respect to FIG. **7**.

At step **515** shown in FIG. **7**, all of the light source intensity values are retrieved or accessed from memory. The stored LED data is also retrieved from memory (step **520**) such that the total output of the light fixture (i.e., the output of each light source) can be calculated (step **525**). For example, the output intensity of each light source with respect to wavelength is determined based on the initial output intensity values for each light source and the LED data. The output intensities of each light source are then combined to produce a set of data corresponding to the total output for the light fixture. The total output of the light fixture is then used to calculate a color space coordinate (step **530**) for the total output of the light fixture based on the initial light source output intensity values and the color matching functions described above. The distance between the total light fixture output color space coordinate and the target color coordinate is then calculated (step **535**) using, for example, EQN. 21 above. The distance calculated at step **535** is compared to a threshold value (step **540**). The threshold value is, for example, a distance value, a percent-error value, a mean square error ("MSE"), or the like. If the distance is not less than or equal to the threshold value, the process **400** proceeds to section DD shown in and described with respect to FIG. **8**. If the initial output intensity values for the light sources resulted in a light fixture output color space coordinate that was less than or equal to the threshold value, the light sources are driven or activated at the stored initial output intensity values (step **545**).

With reference to FIG. **8** and step **550**, a fourth variable, D, is initialized or set equal to one, and the light source variable, LS, is set equal to D (e.g., the first light source) (step **555**). At step **560**, a step size value is added to the output intensity value of the selected light source. The step size value is based on, for example, the separation or distance between the total light fixture output color space coordinate and the target color coordinate (e.g., the step size value is proportional to the separation between the total light fixture output color space coordinate and the target color coordinate). For example, if the distance between the total light fixture output color space coordinate and the target color coordinate is greater than or equal to one or more threshold values, the step size value is set proportionally large. If the distance between the total light fixture output color space coordinate and the target color coordinate is less than or equal to one or more threshold values, the step size value is set proportionally small. In some implementations, the step size value is a percentage value, an incremental intensity value, or the like. For example, if the step size value is 5%, the output intensity value for the light source is increased by 5%. Using the new output intensity value for the selected light source, the previously retrieved initial output intensity values for the remaining light sources (i.e., the un-modified initial output intensity values), and the previously retrieved LED data, the total output of the light fixture is recalculated (step **565**). The color space coordinate for total light fixture output is also recalculated (step **570**). The distance between the new color space coordinate for the total light fixture output and the target color coordinate is calculated (step **575**), and the distance between the new color space coordinate for the total output and the target color coordinate is stored to memory (step **580**). The output intensity value for the selected light source is then reset to the previous (i.e., un-modified) output intensity value (step **585**). The selected light source corresponding to the fourth variable, D, is compared to the number of LEDs in the light fixture (step **590**). If the selected light source is not the last light source in the light fixture, the fourth variable, D, is incremented by one (step **595**) and the light source variable, LS, is reset to the new value of the fourth variable, D (step **555**). The process **400** repeats steps **560-590** until the step size value has been added to each output intensity value for the light sources. If the selected light source is the last light source in the light fixture, the process **400** proceeds to section EE shown in and described with respect to FIG. **9**.

At step **600** in FIG. **9**, a fifth variable, E, is initialized or set equal to one, and the light source variable, LS, is set equal to the fifth variable, E (e.g., the first light source) (step **605**). At step **610**, a step size value is subtracted from the output intensity value of the selected light source. As described above, in some implementations, the step size value is based on the separation or distance between the total light fixture output color space coordinate and the target color coordinate, and the step size value is a percentage value, a decremental intensity value, or the like. For example, if the step size value is 5%, the output intensity value for the light source is decreased by 5%. Using the new output intensity value for the selected light source, the previously retrieved initial output intensity values for the remaining light sources, and the previously retrieved LED data, the total output of the light fixture is recalculated (step **615**). The color space coordinate for total light fixture output is also recalculated (step **620**). The distance between the new color space coordinate for the total light fixture output and the target color coordinate is calculated (step **625**), and the distance between the new color space coordinate for the total output and the target color coordinate is stored in memory (step **630**). The output intensity value for the selected light source is then reset to the previous output intensity value (step **635**). The selected light source corresponding to the fifth variable, E, is compared to the number of LEDs in the light fixture (step **640**). If the selected light source is not the last light source in the light fixture, the fifth variable, E, is incremented by one (step **645**), and the light source variable, LS, is reset to the new value of the fifth variable, E (step **605**). The process **400** repeats steps **610-640** until the step size value has been subtracted from each output intensity value for the light sources. If the selected light source is the last light source in the light fixture, the process **400** proceeds to section FF shown in and described with respect to FIG. **10**. In some implementations, the addition and subtraction of the step size value to the output intensity of each light source are performed consecutively as opposed to adding the step size value to the output intensity of each LED source and then subtracting the step size value from each light source. In other implementations, subtraction of the step size value is performed before the addition of the step size value. Additionally or alternatively, the step size value varies between the addition and subtraction or from light source to light source based on, for example, initial intensity values, a calculated distance, or another feedback criterion.

With reference to FIG. **10**, after the step size value has been added to and subtracted from the stored intensity values for each of the light sources, the stored distances associated with total light fixture output for each of the modified intensity values are retrieved or accessed from memory (step **650**). For example, a seven light source light fixture has fourteen distance values stored in memory corresponding to the addition and subtraction of a step size value from the stored output intensity values for each light source. The retrieved distances are then compared to one another to determine the shortest distance (step **655**). The shortest distance value corresponds to the set of output intensity values that resulted in the least amount of error (i.e., the addition or subtraction of the step size value that resulted in the most beneficial change in the output of the light fixture). After the shortest distance has been identified, the stored output intensity values are modified (step **660**) to correspond to the output intensity values that produced the shortest distance. For example, the step size value is added to or subtracted from a single output intensity value.

After the step size value has been added to or subtracted from the output intensity value, the output intensity values of each of the light sources are normalized (step **665**). For example, modifying the output intensity values as described above can result in each of the light sources having an output intensity value of less than 100.0%. In such an instance, the light source or light sources having the highest output intensity value are normalized to a 100.0% output intensity value. As an illustrative example, a light fixture including seven light sources has output intensity values for each of the light sources (following step **660**) as shown below in Table #1. Because the green light source has the highest output intensity value (i.e., 80.0%), the output intensity value of the green light source is reset to an output intensity value of 100.0%. The increase in the output intensity value of the green light source is 25.0% based on the un-normalized output intensity value. As such, the output intensity values of each of the remaining light sources are also increased by 25.0% based on the un-normalized output intensity values. For example, the red light source has an un-normalized output intensity value of 40.0%. Increasing the output intensity by 25.0% results in a normalized output intensity value of 50.0%. The output intensity values of the light sources are normalized to ensure or at least approximate the combination of light source output intensity values that produces a maximum lumen output (i.e., a maximum luminous flux) for the light fixture. Although the step of normalizing the light source output intensity values is shown following step **660**, the output intensity values can be normalized in the same or a similar manner later in the process **400** (e.g., following step **670**, step **675**, or step **685** (all described below)).

TABLE #1

Normalized Light Source Output Intensity Values		
Color	Un-Normalized Intensity	Normalized Intensity
Red	40.0%	50.0%
Red-Orange	50.0%	62.5%
Amber	60.0%	75.0%
Green	80.0%	100.0%
Cyan	30.0%	37.5%
Blue	10.0%	12.5%
Indigo	20.0%	25.0%

The new output intensity values corresponding to that light sources are then stored in memory (step **670**). The shortest distance is then compared to the threshold value (step **675**). Because the normalization described above modified the output intensities of the light sources by the same amount, the ratios of the light source intensities remain the same. As such, the shortest distance that was determined at step **655** remains unchanged and does not need to be recalculated following the normalization of step **665**. As described above, the threshold value is, for example, a distance value, a percent-error value, or the like. If the distance is not less than or equal to the threshold value, the process **400** proceeds to section GG shown in and described with respect to FIG. **8** where the new intensity values are retrieved from memory (step **680**) and a step size value is again added to and subtracted from the new stored output intensity values. If the distance is less than the threshold value, the new light source intensity values are retrieved or accessed from memory (step **685**), and the light sources are driven or activated at the stored output intensity values (step **690**). Additionally, because the process **400** is capable of being executed by the light fixture itself and no powerful central computer is required, each light fixture in a system of light fixtures is capable of executing the process **400** in a parallel manner.

The process **400** can be performed or executed following, for example, receiving a set of input parameters, a determined change in the intensity value, a determined change in the white point, or the like. As such, additional modified target color points can be calculated based on a modification to the intensity value and without modification to the desired target color. For example, after a first modified target color coordinate has been identified, a change in the intensity value causes, among other things, a new white point color temperature and white point color coordinate to be identified, a new color temperature transformation to be selected, and a new modified target color coordinate to be calculated. Additionally or alternatively, the process **400** can be preformed each time a signal related to the input parameters is received (e.g., even if none of the values associated with those signals have changed).

Thus, the invention provides, among other things, systems and methods for controlling an output of a light fixture to mimic the color temperature changes of an ideal black-body radiator. Various features and advantages of the invention are set forth in the following claims.

What is claimed is:

1. A method of controlling an output of a light fixture, the light fixture including four or more light sources, the method comprising:

receiving a first input parameter corresponding to a first color point within a color space;

receiving a second input parameter associated with a desired intensity for the first color point;

determining a white point based on a relationship between the second input parameter and the color temperature of a black-body radiator, the white point corresponding to a second color point within the color space;

selecting a color temperature transform based on the white point;

calculating a third color point within the color space based on the color temperature transform, the color temperature transform defining a relationship between the first color point and the third color point, the third color point being different than the first color point, and the third color point being different than the second color point;

determining a respective light source output value for each of the four or more light sources based on the third color point; and

driving each of the four or more light sources at the respective light source output value to produce the output of the light fixture.

2. The method of claim **1**, wherein the relationship between the second input parameter and the color temperature of the black-body radiator includes a linear approximation of the color temperature of the black-body radiator.

3. The method of claim **1**, wherein the second color point substantially lies on the Planckian locus, the first color point does not substantially lie on the Planckian locus, and the third color point does not substantially lie on the Planckian locus.

4. The method of claim **1**, further comprising

receiving a third input parameter associated with a second desired intensity of the first color point; and

determining a second white point based on a relationship between the third input parameter and the color temperature of the black-body radiator, the second white point corresponding to a fourth color point within the color space.

5. The method of claim **4**, further comprising

selecting a second color temperature transform based on the second white point; and

calculating a fifth color point within the color space based on the second color temperature transform, the second color temperature transform defining a relationship between the third color point and the fifth color point, the fifth color point being different than the third color point, and the fifth color point being different than the fourth color point.

6. The method of claim **5**, further comprising

determining a second respective light source output value for each of the four or more light sources based on the fifth color point; and

driving each of the four or more light sources at the second respective light source output value to produce the output of the light fixture.

7. The method of claim **5**, wherein the fourth color point substantially lies on the Planckian locus and the fifth color point does not substantially lie on the Planckian locus.

8. A method of controlling an output of a light fixture, the light fixture including four or more light sources, the method comprising:

receiving a set of input parameters, the set of input parameters corresponding to a first color point within a color space and an intensity for the first color point;

determining a color temperature setting based on a relationship between the set of input parameters and the color temperature of a black-body radiator, the color temperature setting corresponding to a second color point within the color space;

determining a color temperature transform based on the color temperature setting;

calculating a third color point within the color space based on the color temperature transform, the color temperature transform defining a relationship between the first color point and the third color point, the third color point being different than the first color point, and the third color point being different than the second color point;

determining a respective light source output value for each of the four or more light sources based on the third color point; and

driving each of the four or more light sources at the respective light source output value to produce the output of the light fixture.

9. The method of claim **8**, wherein the second color point substantially lies on the Planckian locus, the first color point does not substantially lie on the Planckian locus, and the third color point does not substantially lie on the Planckian locus.

10. The method of claim **8**, further comprising

receiving a second set of input parameters corresponding to the first color point and a second intensity for the first color point; and

determining a second white point based on a relationship between the second set of input parameters and the color temperature of the black-body radiator, the second white point corresponding to a fourth color point within the color space.

11. The method of claim **10**, further comprising

selecting a second color temperature transform based on the second white point; and

calculating a fifth color point within the color space based on the second color temperature transform, the second color temperature transform defining a relationship between the third color point and the fifth color point, the fifth color point being different than the third color point, and the fifth color point being different than the fourth color point.

12. The method of claim **11**, further comprising

determining a second respective light source output value for each of the four or more light sources based on the fifth color point; and

driving each of the four or more light sources at the second respective light source output value to produce the output of the light fixture.

13. The method of claim **11**, wherein the fourth color point substantially lies on the Planckian locus and the fifth color point does not substantially lie on the Planckian locus.

14. A system for controlling the output of a light fixture, the system including:

four or more light sources; and

a controller configured to

receive a first input parameter corresponding to a first color point within a color space,

receive a second input parameter associated with a desired intensity for the first color point,

determine a white point based on a relationship between the second input parameter and the color temperature of a black-body radiator, the white point corresponding to a second color point within the color space,

select a color temperature transform based on the white point,

calculate a third color point within the color space based on the color temperature transform, the color temperature transform defining a relationship between the first color point and the third color point, the third color point being different than the first color point, and the third color point being different than the second color point,

determine a respective light source output value for each of the four or more light sources based on the third color point, and drive each of the four or more light sources at the respective light source output value to produce the output of the light fixture.

15. The system of claim **14**, wherein the relationship between the second input parameter and the color temperature of the black-body radiator includes a linear approximation of the color temperature of the black-body radiator.

16. The system of claim **14**, wherein the second color point substantially lies on the Planckian locus, the first color point does not substantially lie on the Planckian locus, and the third color point does not substantially lie on the Planckian locus.

17. The system of claim **14**, wherein the controller is further configured to

receive a third input parameter associated with a second desired intensity of the first color point, and

determine a second white point based on a relationship between the third input parameter and the color temperature of the black-body radiator, the second white point corresponding to a fourth color point within the color space.

18. The system of claim **17**, wherein the controller is further configured to

select a second color temperature transform based on the second white point, and

calculate a fifth color point within the color space based on the second color temperature transform, the second color temperature transform defining a relationship between the third color point and the fifth color point, the fifth color point being different than the third color point, and the fifth color point being different than the fourth color point.

19. The system of claim **18**, wherein the controller is further configured to

determine a second respective light source output value for each of the four or more light sources based on the fifth color point, and

drive each of the four or more light sources at the second respective light source output value to produce the output of the light fixture.

20. The system of claim **18**, wherein the fourth color point substantially lies on the Planckian locus and the fifth color point does not substantially lie on the Planckian locus.

* * * * *

Exhibit B

US011240898B2

(12) United States Patent
Florac et al.

(10) **Patent No.: US 11,240,898 B2**
(45) **Date of Patent: Feb. 1, 2022**

(54) **SYSTEMS, METHODS, AND DEVICES FOR INFLUENCING SPECTRAL CONTENT OF A LIGHT OUTPUT**

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(72) Inventors: **William R. Florac**, Verona, WI (US); **Evan Gnam**, Madison, WI (US); **Wendy Luedtke**, Brooklyn, NY (US); **James Uphoff**, Madison, WI (US)

(73) Assignee: **Electronic Theatre Controls, Inc.**, Middleton, WI (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **17/173,286**

(22) Filed: **Feb. 11, 2021**

(65) **Prior Publication Data**

US 2021/0251064 A1 Aug. 12, 2021

Related U.S. Application Data

(60) Provisional application No. 62/975,459, filed on Feb. 12, 2020.

(51) **Int. Cl.**
H05B 45/20 (2020.01)
H05B 47/11 (2020.01)

(52) **U.S. Cl.**
CPC ***H05B 47/11*** (2020.01); ***H05B 45/20*** (2020.01)

(58) **Field of Classification Search**
CPC H05B 45/20; H05B 45/14; H05B 47/10; H05B 47/11; H05B 47/105; H05B 47/115; Y02B 20/40
See application file for complete search history.

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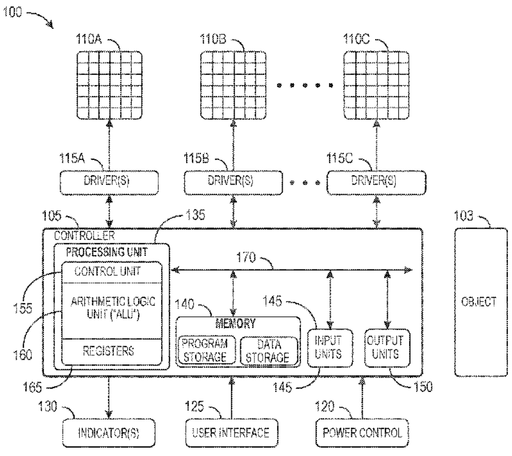
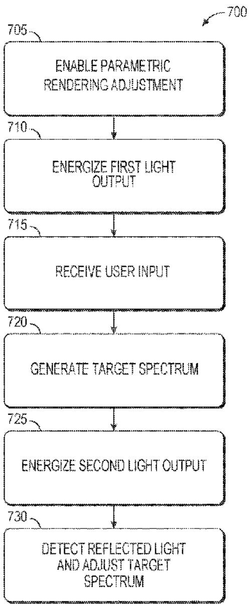
Primary Examiner — Haissa Philogene
(74) *Attorney, Agent, or Firm* — Michael Best and Friedrich LLP

(57) **ABSTRACT**

A method for control of a light fixture, the method including energizing the light fixture to produce a first light output with a first chromaticity and a first spectral power distribution, receiving a user input representative of a desired adjustment of a lighting effect, generating a target spectrum based on the user input, and energizing the light fixture to produce a second light output with the first chromaticity and a second spectral power distribution. The second power distribution approximates the target spectrum.

20 Claims, 10 Drawing Sheets





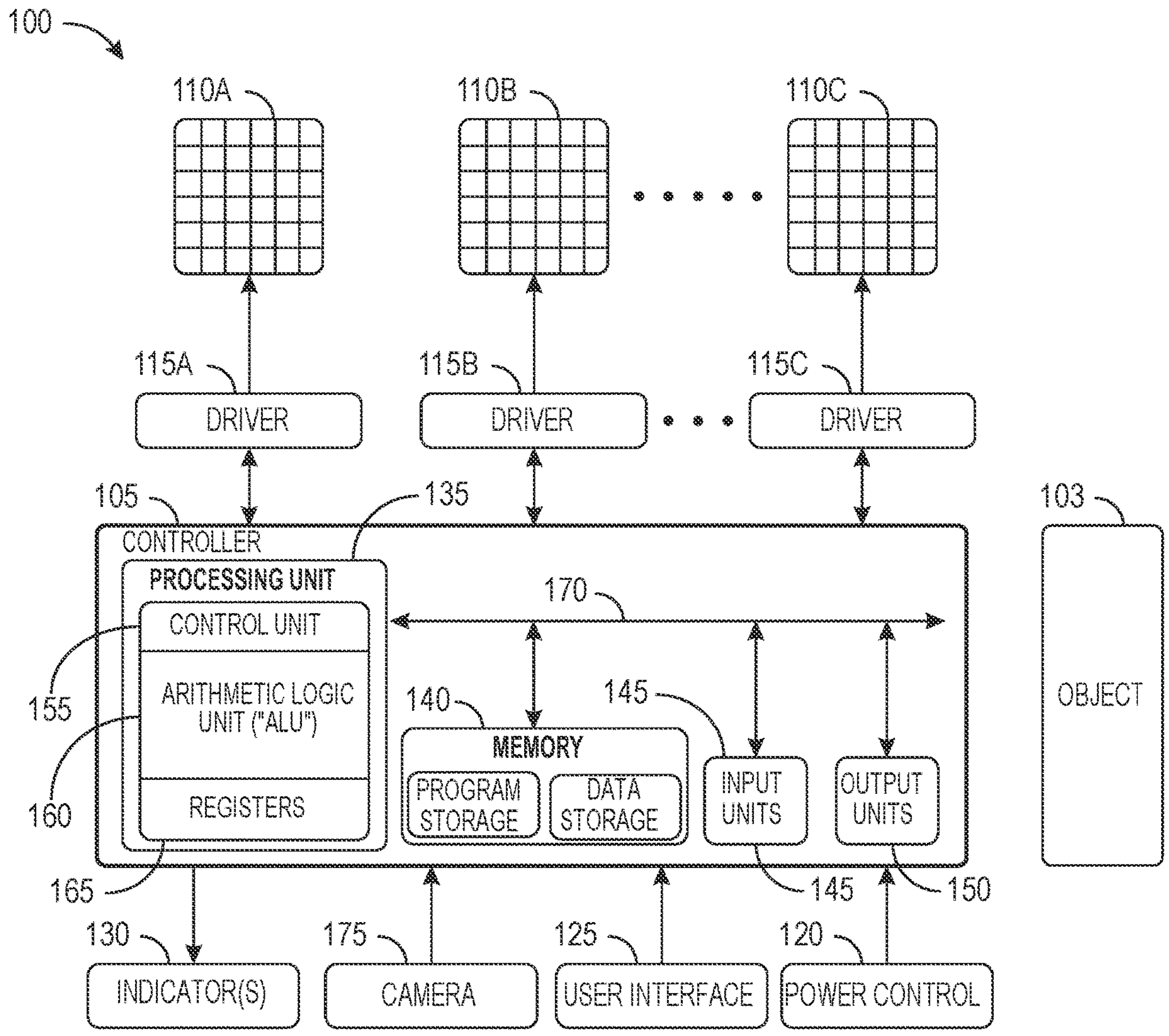

100
110A
110B
110C
115A
115B
115C
DRIVER
DRIVER
DRIVER
105
135
103
CONTROLLER
PROCESSING UNIT
CONTROL UNIT
ARITHMETIC LOGIC UNIT ("ALU")
REGISTERS
170
140
145
MEMORY
PROGRAM STORAGE
DATA STORAGE
INPUT UNITS
OUTPUT UNITS
OBJECT
155
160
165
145
150
130
175
125
120
INDICATOR(S)
CAMERA
USER INTERFACE
POWER CONTROL

FIG. 1

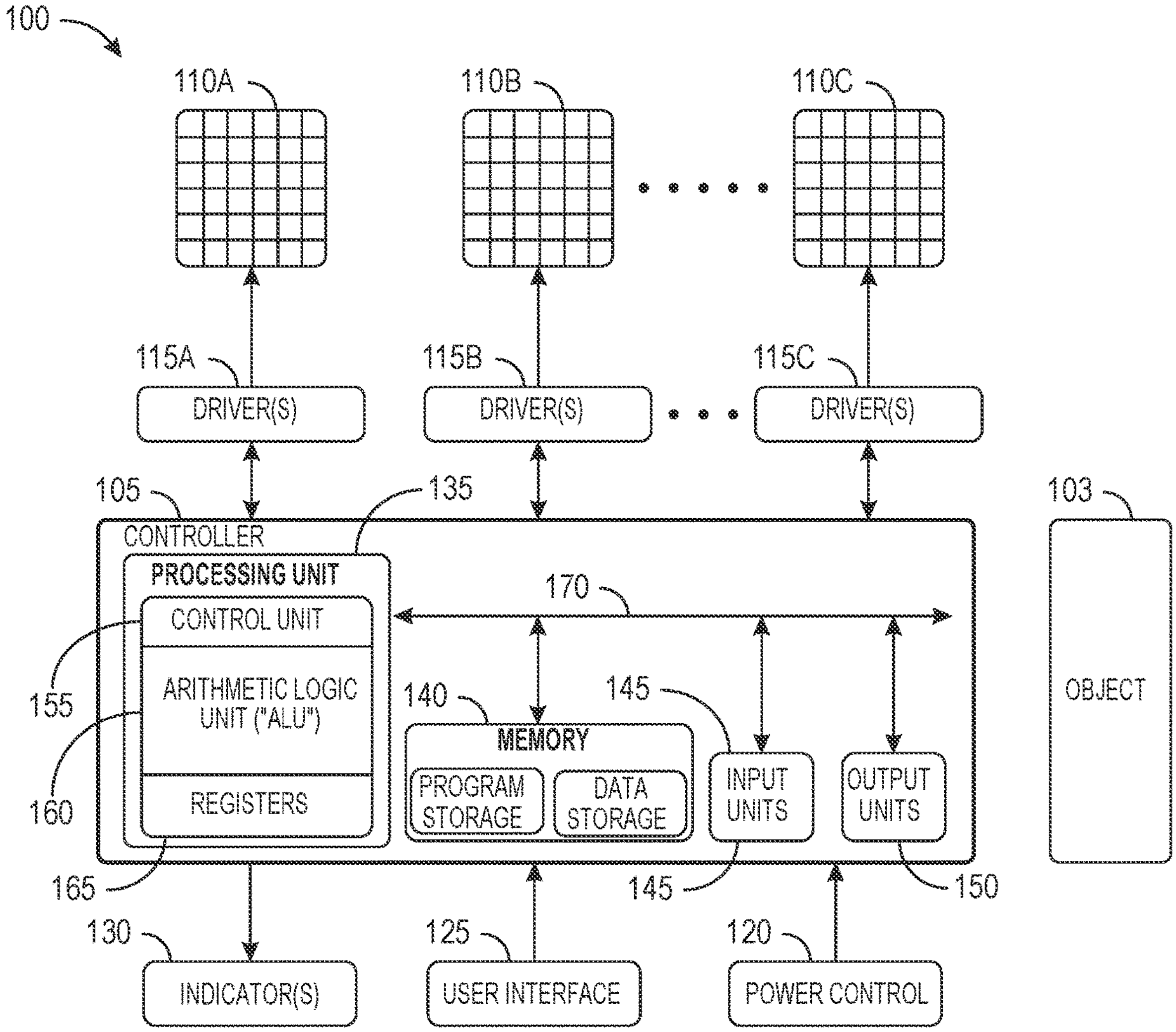

100
110A
110B
110C
115A
115B
115C
DRIVER(S)
DRIVER(S)
DRIVER(S)
105
135
103
CONTROLLER
PROCESSING UNIT
CONTROL UNIT
ARITHMETIC LOGIC UNIT ("ALU")
REGISTERS
170
140
145
MEMORY
PROGRAM STORAGE
DATA STORAGE
INPUT UNITS
OUTPUT UNITS
OBJECT
155
160
165
145
150
130
125
120
INDICATOR(S)
USER INTERFACE
POWER CONTROL

FIG. 2

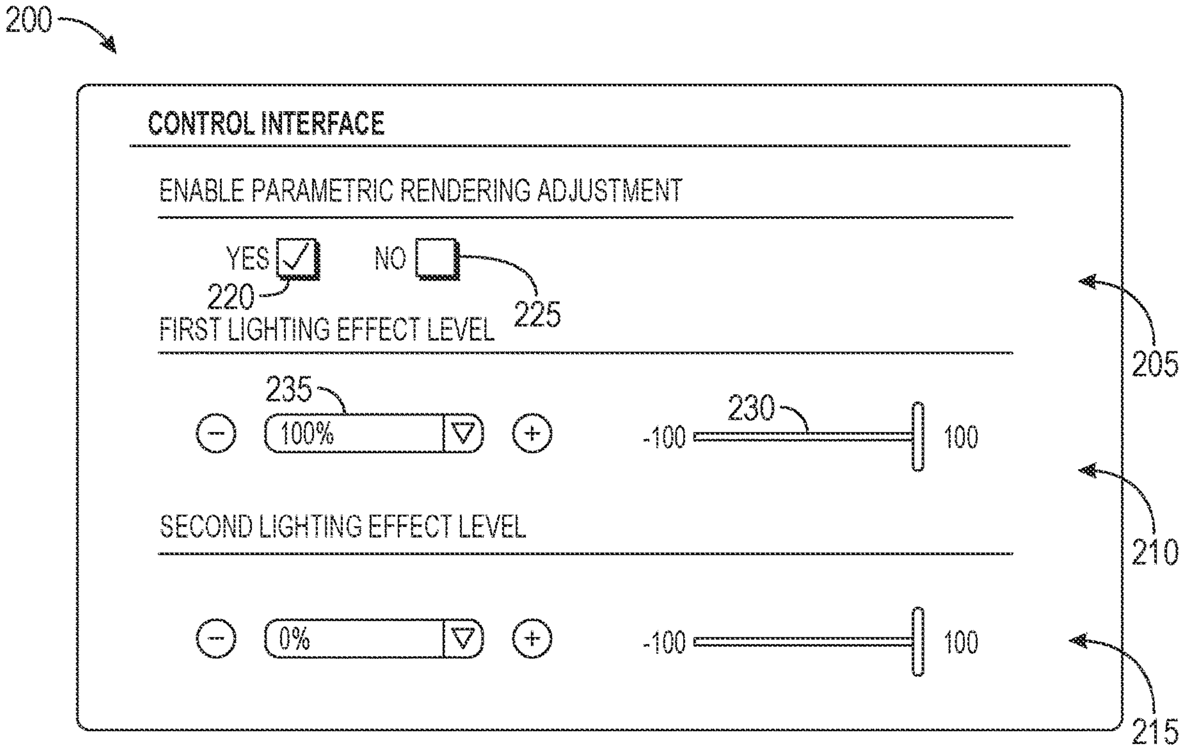

200
CONTROL INTERFACE
ENABLE PARAMETRIC RENDERING ADJUSTMENT
YES ☑
NO ☐
220
225
FIRST LIGHTING EFFECT LEVEL
235
100%
230
-100
100
SECOND LIGHTING EFFECT LEVEL
0%
-100
100
205
210
215

FIG. 3

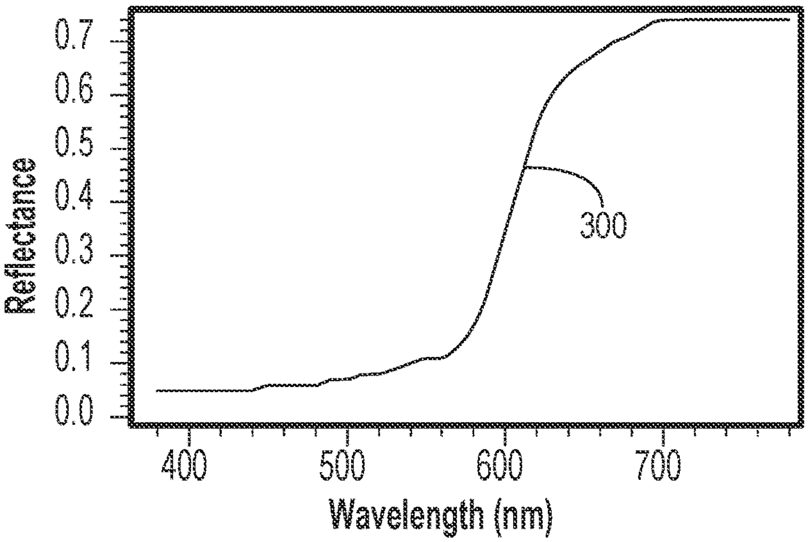

Reflectance
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
400
500
600
700
Wavelength (nm)
300

FIG. 4

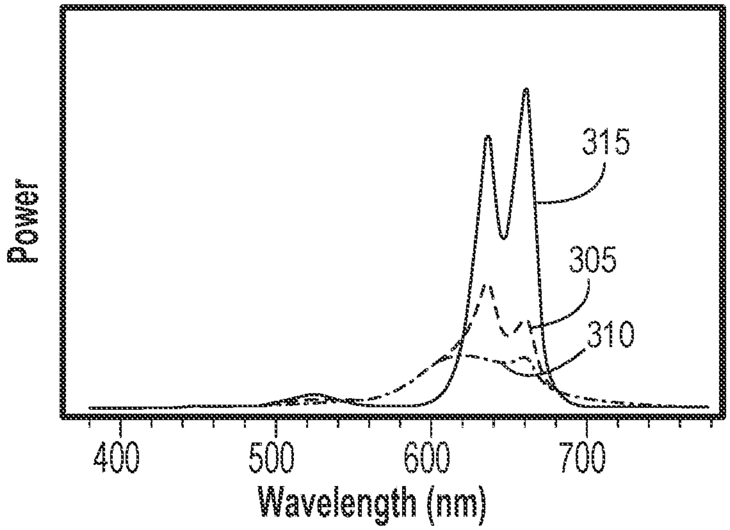

315
305
310
Power
400
500
600
700
Wavelength (nm)

FIG. 5

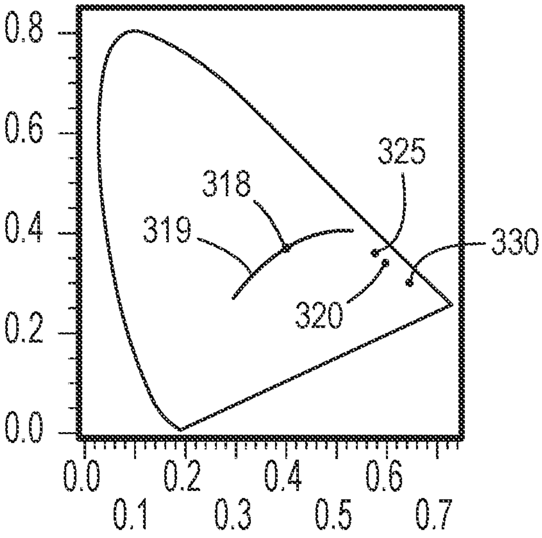

0.8
0.6
0.4
0.2
0.0
325
318
319
330
320
0.0
0.2
0.4
0.6
0.1
0.3
0.5
0.7

FIG. 6

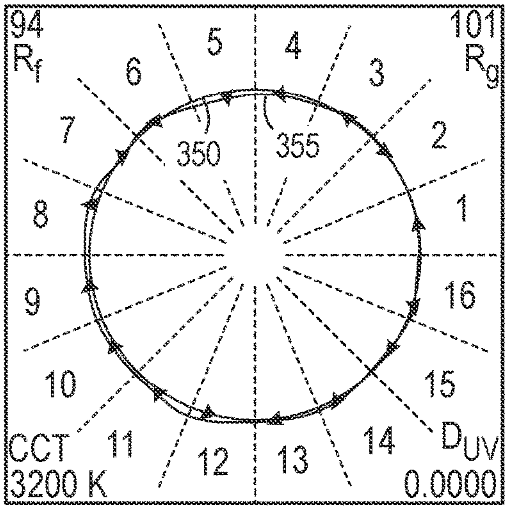


FIG. 7A

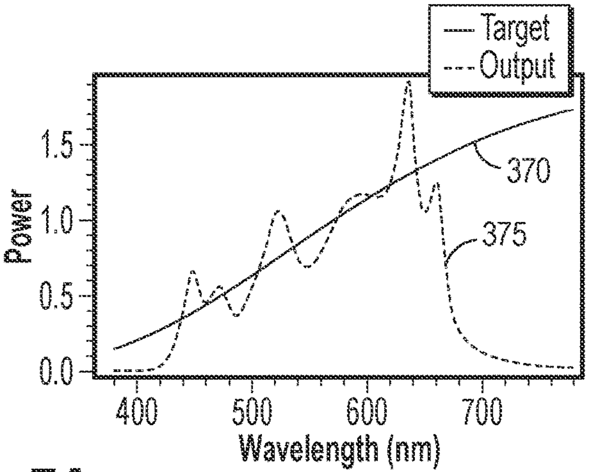


FIG. 8A

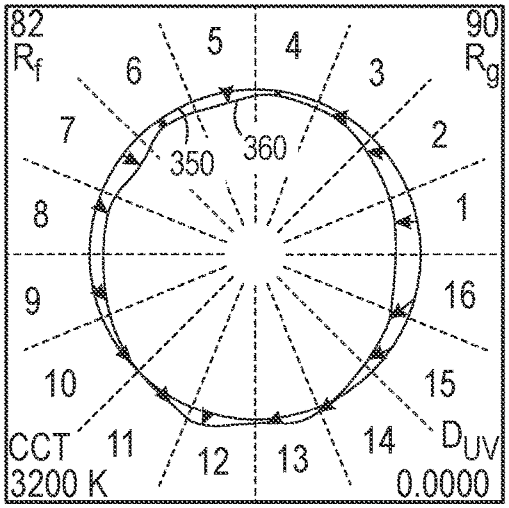


FIG. 7B

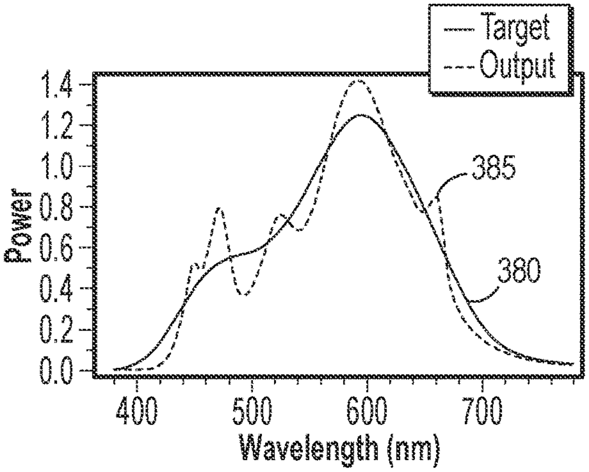


FIG. 8B

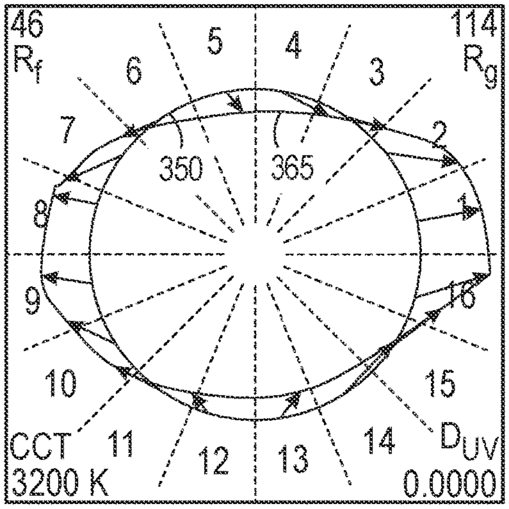


FIG. 7C

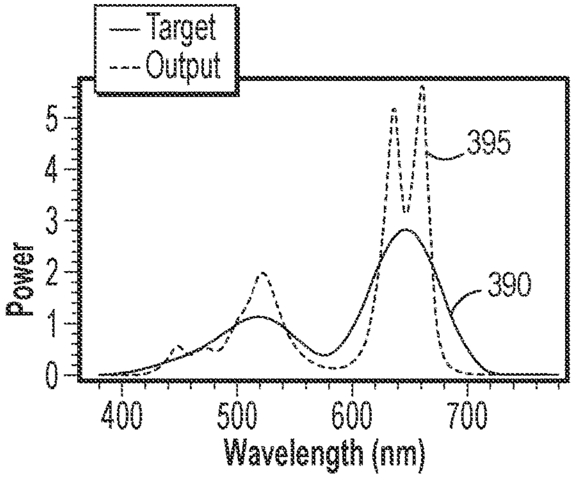


FIG. 8C

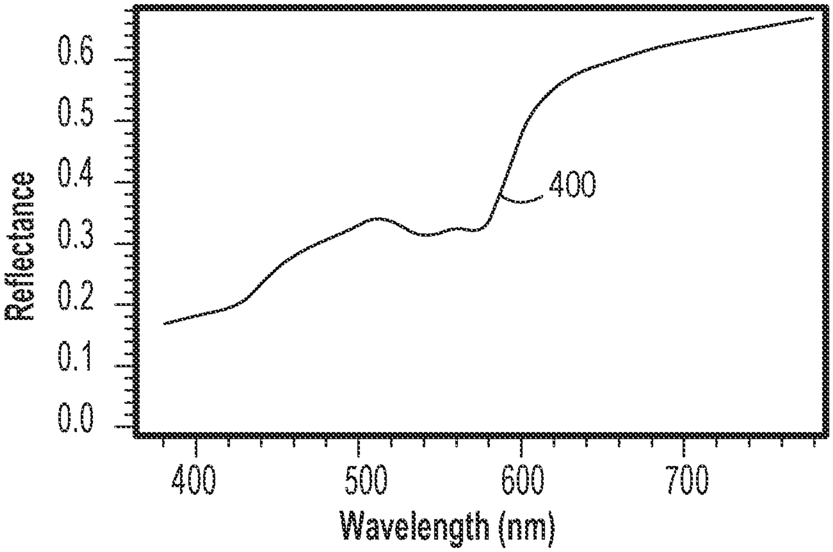

0.6
0.5
0.4
0.3
0.2
0.1
0.0
Reflectance
400
400
500
600
700
Wavelength (nm)

FIG. 9

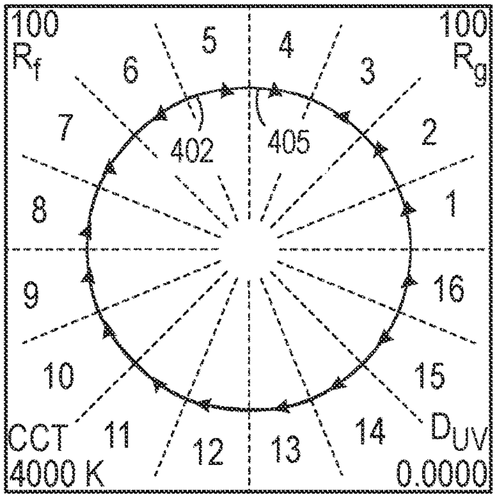


FIG. 10A

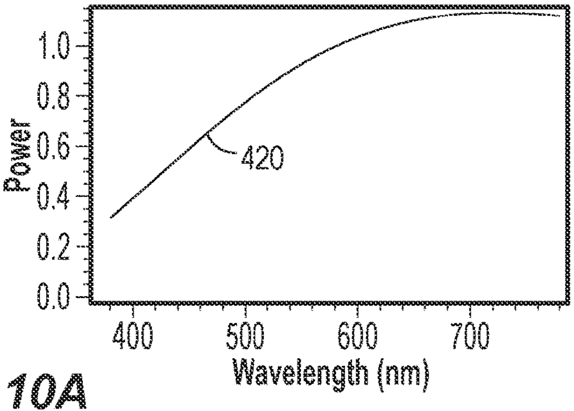


FIG. 11A

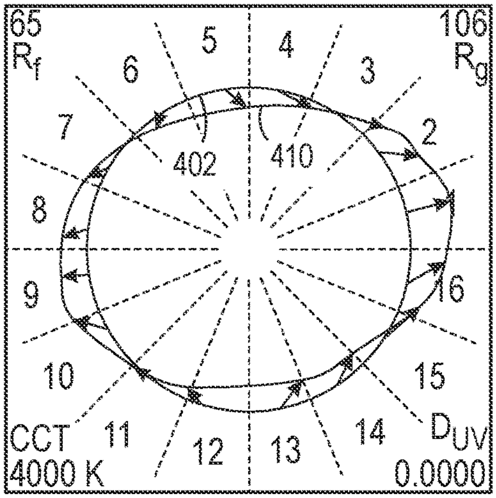


FIG. 10B

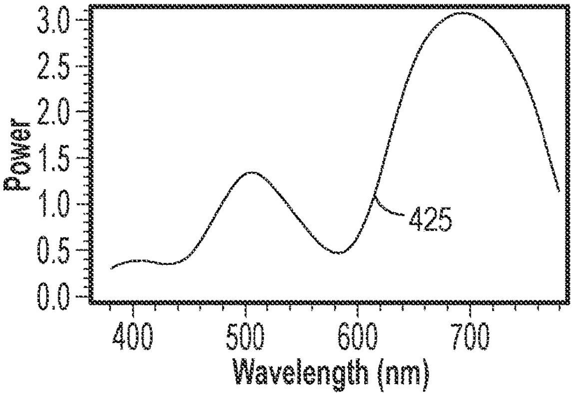


FIG. 11B

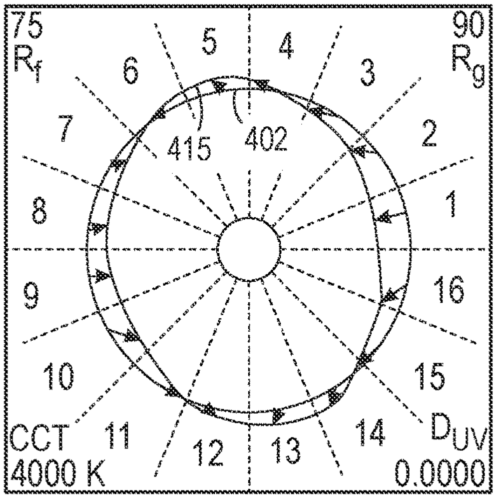


FIG. 10C

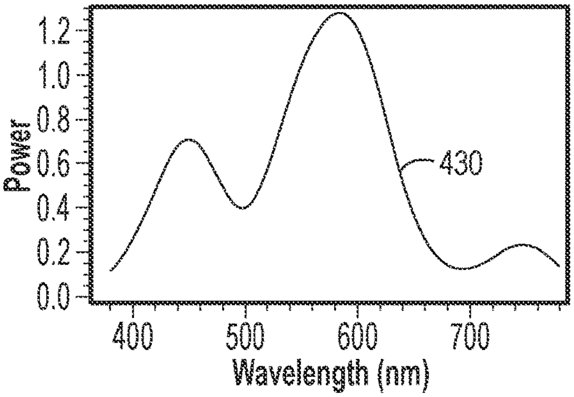


FIG. 11C

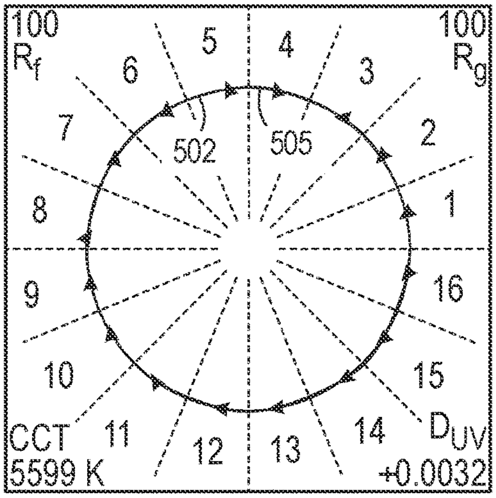


FIG. 12A

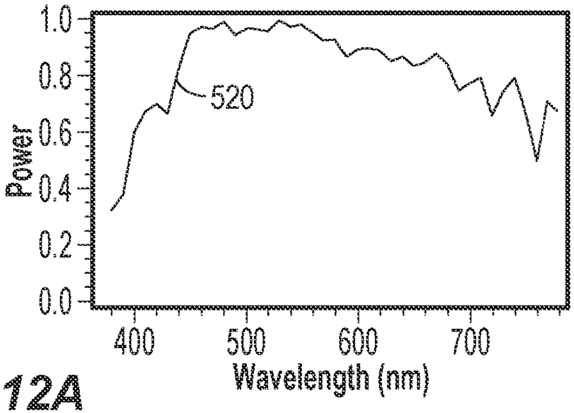


FIG. 13A

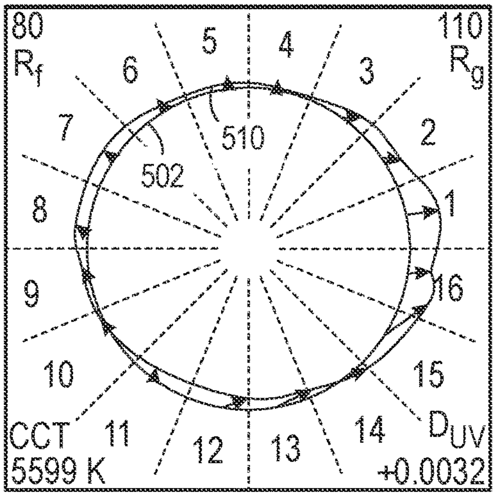


FIG. 12B

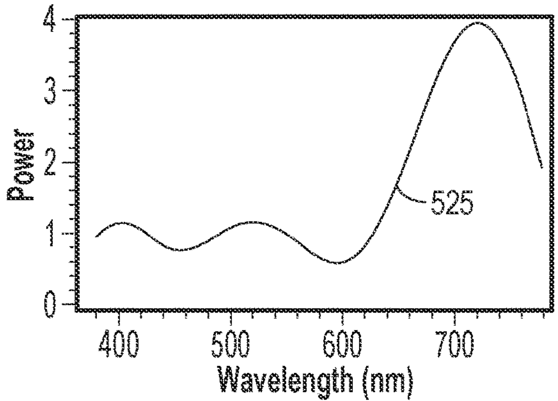


FIG. 13B

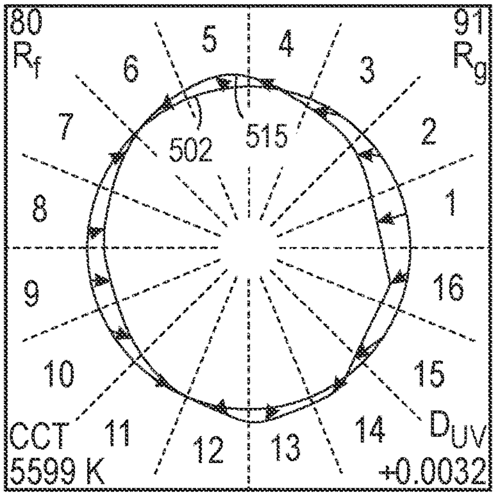


FIG. 12C

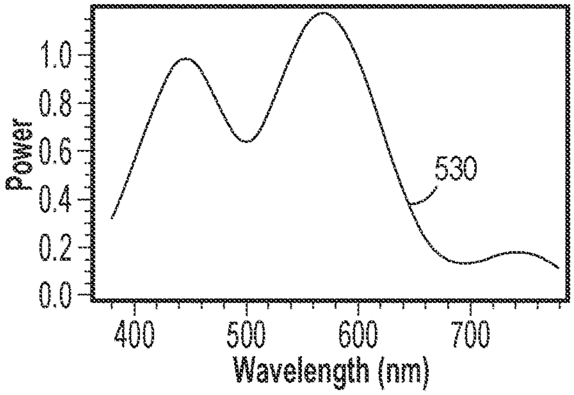


FIG. 13C

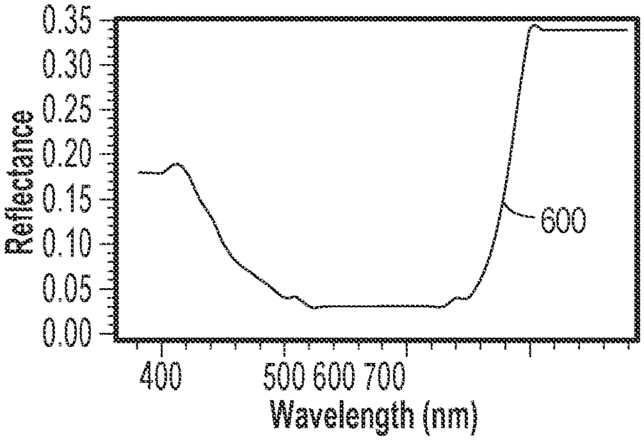


FIG. 14

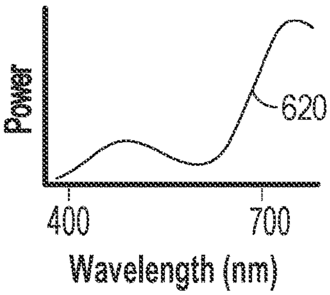


FIG. 15A

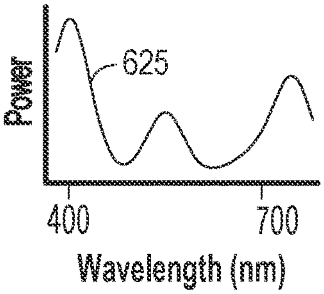


FIG. 15B

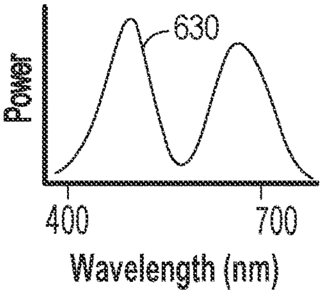


FIG. 15C

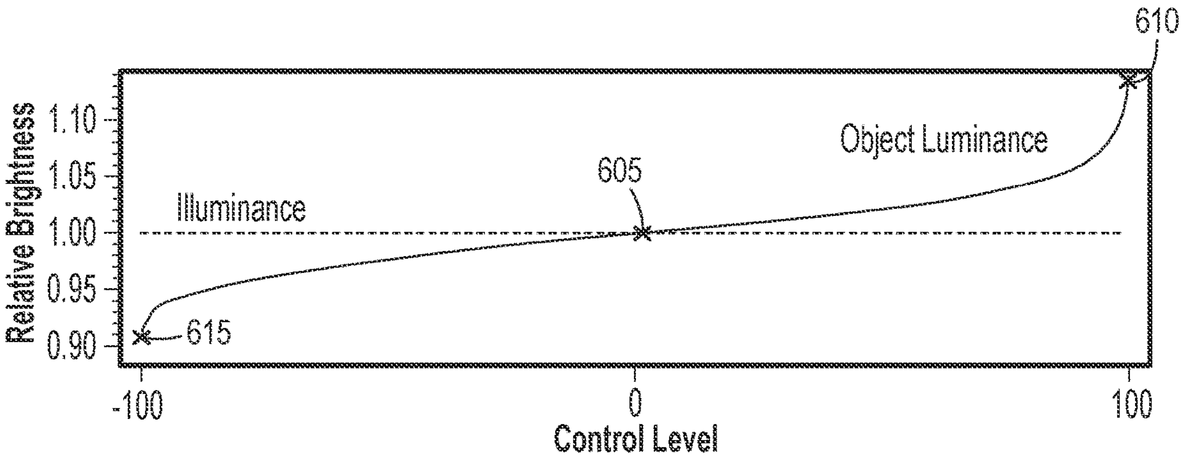


FIG. 16

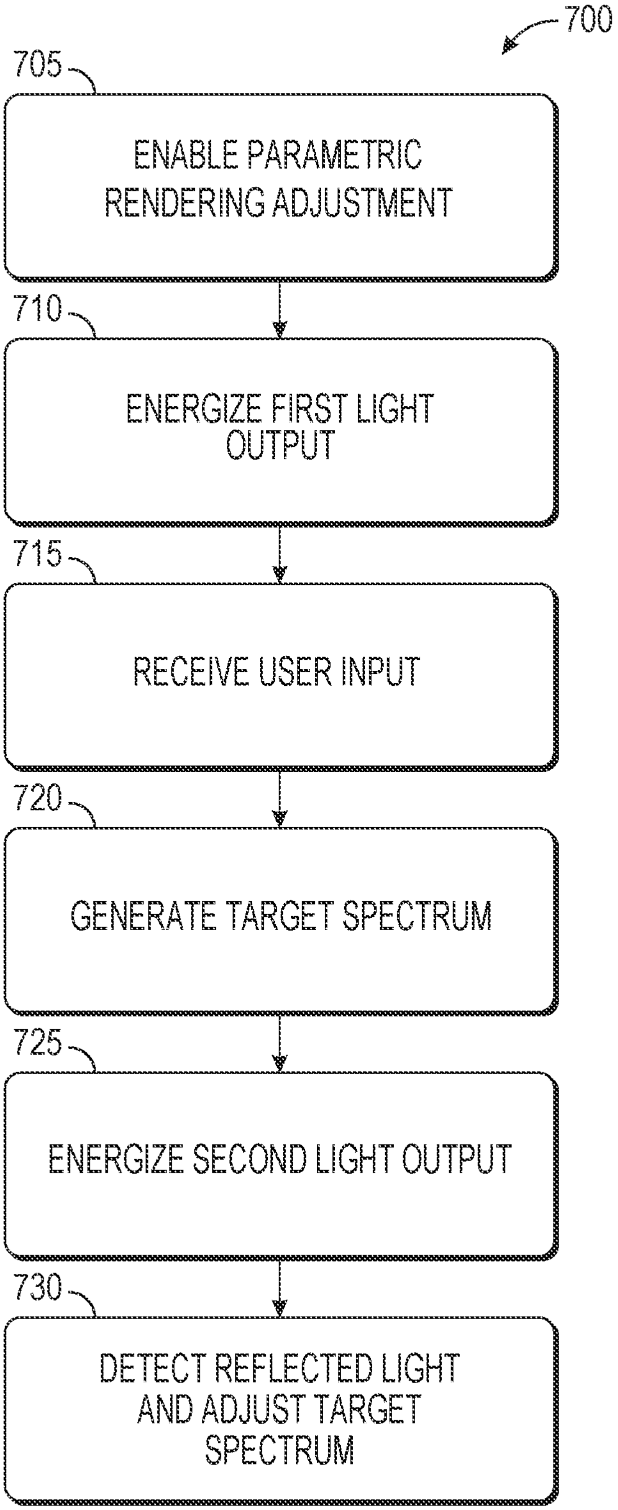

700
705
ENABLE PARAMETRIC RENDERING ADJUSTMENT
710
ENERGIZE FIRST LIGHT OUTPUT
715
RECEIVE USER INPUT
720
GENERATE TARGET SPECTRUM
725
ENERGIZE SECOND LIGHT OUTPUT
730
DETECT REFLECTED LIGHT AND ADJUST TARGET SPECTRUM

FIG. 17

SYSTEMS, METHODS, AND DEVICES FOR INFLUENCING SPECTRAL CONTENT OF A LIGHT OUTPUT

CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims priority to U.S. Provisional Patent Application No. 62/975,459, filed Feb. 12, 2020, the entire contents of which are hereby incorporated by reference herein.

FIELD

Embodiments described herein relate to influencing the spectral content of a light output.

BACKGROUND

Lighting systems used in architecture, theaters, concert stages, and other applications may be configured to control the light produced by a light source, such as a light fixture, luminaire, array of light emitting diodes, or other lighting device.

SUMMARY

The lighting system may be controlled in various ways to produce a desired chromaticity (i.e., color) for the output light. Holding the chromaticity of the light output while adjusting the spectral content of the light output is called metameric control. For example, U.S. Pat. No. 8,723,450, incorporated herein by reference, discloses controlling the spectral content of the output of a light fixture by modifying the output intensity value of one or more of the light sources that make up the light fixture. For example, the user may adjust upwards the power output of a red light emitting diode ("LED") within the light fixture. After modifying the output intensity values of individual emitters, a color control and matching technique is used to identify a new set of output intensity values for the remaining emitters that maintains the desired color output. The method of adjusting spectral content of a light output disclosed in U.S. Pat. No. 8,723,450 is specific to a given light fixture because the control adjusts the output of the specific light sources (e.g., individual LED) contained within the light fixture. However, different light fixtures have different light sources, so the method disclosed in U.S. Pat. No. 8,723,450 is not readily applicable or generic across different light fixtures. Finally, although the user is able to adjust the spectral content of the light output in the method disclosed in U.S. Pat. No. 8,723,450, the user is not provided control over or insight into how, for example, an object will appear when illuminated by the light output with the modified spectral content. In other words, the user is able to adjust the spectral content of the light output in U.S. Pat. No. 8,723,450 but does not have control over the lighting effect or effects (i.e., as perceived by a human observer or camera observer) created by the changing spectral content.

Embodiments described herein address this and other technical problems by analyzing aspects of perceived light to adjust the perceived appearance of the light output according to user specifications. The aspects of the perceived light controlled by embodiments described herein may include, for example, how the user perceives an object within the light output. In this way, the user alters the look and/or feel of the object according to how the user wants the object to appear. As a result, the user can alter how the object appears without altering the chromaticity of the light output. For example, the user may desire the object (e.g., human skin) to appear sickly under a metameric (constant-chromaticity) illuminant, or to appear brighter under a constant-power illuminant, or both.

Methods described herein provide for control of a light fixture, the method including energizing the light fixture to produce a first light output with a first chromaticity and a first spectral power distribution, receiving a user input representative of a desired adjustment of a lighting effect, generating a target spectrum based on the user input, and energizing the light fixture to produce a second light output with the first chromaticity and a second spectral power distribution. The second power distribution approximates the target spectrum.

Lighting control systems described herein include one or more light fixtures, one or more driver circuits, a user interface, and a controller. The one or more driver circuits are configured to provide drive signals to the one or more light fixtures. The user interface is configured to receive an input related to a light output of the one or more light fixtures. The input is representative of an adjustment of a lighting effect. The controller is connected to the one or more driving circuits and the user interface. The controller includes a processor and a memory. The controller is configured to energize the one or more light fixtures to produce a first light output with a first chromaticity and a first spectral power distribution, receive the input representative of the adjustment of the lighting effect, generate a target spectrum based on the input, and energize the one or more light fixtures to produce a second light output with the first chromaticity and a second spectral power distribution, the second power distribution approximates the target spectrum.

Controllers for controlling a light output of a light fixture described herein include a non-transitory computer readable medium and a processor. The controller includes computer executable instructions stored in the computer readable medium for controlling operation of the controller to energize the light fixture to produce a first light output with a first chromaticity and a first spectral power distribution, receive an input representative of an adjustment of a lighting effect, generate a target spectrum based on the user input, and energize the light fixture to produce a second light output with the first chromaticity and a second spectral power distribution, the second power distribution approximates the target spectrum.

It should be understood that the terms spectral match, spectrally matching, and the like (including similar terms with fixed or constant) refer to the application of an optimization procedure for spectrally matching the output composite light spectrum of the composite light source to a given target spectrum. It should be understood that the spectral match provided by the composite light source will not necessarily be identical to the target spectrum. But, it will be optimally close or as close as possible according to given system constraints. Similarly, the terms chromaticity match, chromaticity matching, constant chromaticity, fixed chromaticity, and the like refer to the application of an optimization procedure for matching CIE chromaticity coordinates of the output composite light source spectrum to CIE chromaticity coordinates of a given target spectrum. It should be understood that the chromaticity match provided by the composite light source will not necessarily be identical to the target spectrum. But, it will be optimally close or as close as possible according to given system constraints.

Before any embodiments are explained in detail, it is to be understood that the embodiments are not limited in their application to the details of the configuration and arrangement of components set forth in the following description or illustrated in the accompanying drawings. The embodiments are capable of being practiced or of being carried out in various ways. Also, it is to be understood that the phraseology and terminology used herein are for the purpose of description and should not be regarded as limiting. The use of “including,” “comprising,” or “having” and variations thereof are meant to encompass the items listed thereafter and equivalents thereof as well as additional items. Unless specified or limited otherwise, the terms “mounted,” “connected,” “supported,” and “coupled” and variations thereof are used broadly and encompass both direct and indirect mountings, connections, supports, and couplings.

In addition, it should be understood that embodiments may include hardware, software, and electronic components or modules that, for purposes of discussion, may be illustrated and described as if the majority of the components were implemented solely in hardware. However, one of ordinary skill in the art, and based on a reading of this detailed description, would recognize that, in at least one embodiment, the electronic-based aspects may be implemented in software (e.g., stored on non-transitory computer-readable medium) executable by one or more processing units, such as a microprocessor and/or application specific integrated circuits (“ASICs”). As such, it should be noted that a plurality of hardware and software based devices, as well as a plurality of different structural components, may be utilized to implement the embodiments. For example, “servers” and “computing devices” described in the specification can include one or more processing units, one or more computer-readable medium modules, one or more input/output interfaces, and various connections (e.g., a system bus) connecting the components.

Other aspects of the embodiments will become apparent by consideration of the detailed description and accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a block diagram of a lighting control system.

FIG. **2** is a block diagram of a lighting control system according to another embodiment.

FIG. **3** illustrates a control interface for a lighting system.

FIG. **4** is a graph of the spectral reflectance function for an object.

FIG. **5** is a graph illustrating the spectral power distribution of light reflected off the object of FIG. **4** under a default condition, a positive hue shift condition, and a negative hue shift condition.

FIG. **6** is a CIE 1931 chromaticity diagram illustrating the chromaticity of the object of FIG. **4** under the default condition, the positive hue shift condition, and the negative hue shift condition of FIG. **5**.

FIG. **7**A is a TM-30 color vector graphic for the default condition of FIG. **5**.

FIG. **7**B is a TM-30 color vector graphic for the positive hue shift condition of FIG. **5**.

FIG. **7**C is a TM-30 color vector graphic for the negative hue shift condition of FIG. **5**.

FIG. **8**A is a graph illustrating a target output spectral power distribution and an achieved output spectral power distribution for the default condition of FIG. **5**.

FIG. **8**B is a graph illustrating a target output spectral power distribution and an achieved output spectral power distribution for the positive hue shift condition of FIG. **5**.

FIG. **8**C is a graph illustrating a target output spectral power distribution and an achieved output spectral power distribution for the negative hue shift condition of FIG. **5**.

FIG. **9** is a graph of the spectral reflectance function of an object.

FIG. **10**A is a TM-30 color vector graphic for a default condition for the object of FIG. **9**.

FIG. **10**B is a TM-30 color vector graphic for a positive chroma shift condition for the object of FIG. **9**.

FIG. **10**C is a TM-30 color vector graphic for a negative chroma shift condition for the object of FIG. **9**.

FIG. **11**A is a graph illustrating a target output spectral power distribution for the default condition of FIG. **10**A.

FIG. **11**B is a graph illustrating a target output spectral power distribution for the positive chroma shift condition of FIG. **10**B.

FIG. **11**C is a graph illustrating a target output spectral power distribution for the negative chroma shift condition of FIG. **10**C.

FIG. **12**A is a TM-30 color vector graphic for a default condition for a 5600K illuminant.

FIG. **12**B is a TM-30 color vector graphic for an oversaturated condition for the 5600K illuminant.

FIG. **12**C is a TM-30 color vector graphic for an undersaturated condition for the 5600K illuminant.

FIG. **13**A is a graph illustrating a target output spectral power distribution for the default condition of FIG. **12**A.

FIG. **13**B is a graph illustrating a target output spectral power distribution for the oversaturation condition of FIG. **12**B.

FIG. **13**C is a graph illustrating a target output spectral power distribution for the undersaturation condition of FIG. **12**C.

FIG. **14** is a graph of the spectral reflectance function of an object.

FIG. **15**A is a target output spectral power distribution for a non-white chromaticity at a default illuminance of the object of FIG. **14**.

FIG. **15**B is a target output spectral power distribution for the non-white chromaticity at an increased illuminance of the object of FIG. **14**.

FIG. **15**C is a target output spectral power distribution for the non-white chromaticity at a decreased illuminance of the object of FIG. **14**.

FIG. **16** is a graph illustrating the relative brightness of the object of FIG. **14**

FIG. **17** is a method for controlling a light output for a lighting system.

DETAILED DESCRIPTION

FIGS. **1** and **2** illustrate a control system **100** that can be used in, for example, a theatre, a hall, an auditorium, a hotel, a cruise ship, or the like. In some embodiments, the control system **100** is disposed within a light fixture. In other embodiments, only a portion of the control system **100** is disposed in the light fixture. The control system **100** is configured to generate a light output and project that light output onto an object **103** according to specifications of a user for how the object **103** is to appear in the light output. The object **103** may be a human (e.g., skin), an inanimate object (e.g., fruit or fabric), a wall, or the like. Additionally, the light output may be projected onto a plurality of objects **103** (e.g., a class of objects). For descriptive purposes, light is generally described as being projected onto the object **103**. However, in any instance where the object **103** is referenced, light can additionally be projected onto a plurality of objects **103** of the same or different classes of objects. The user specifications may alter the look and/or feel of the object **103** according to how the user wants the object to appear, which allows the user to alter how the object appears without altering the chromaticity of the light output.

The control system **100** includes a controller **105**, a plurality of light modules or light arrays **110**A-**110**C (e.g., light fixtures, color channels, etc.), a plurality of driver circuits **115**A-**115**C, a power control circuit **120**, an input mechanism **125**, and one or more indicators **130**. The controller **105** includes a plurality of electrical and electronic components that provide power, operational control, and protection to the components and modules within the controller **105** and/or the system **100**. For example, the controller **105** includes, among other things, a processing unit **135** (e.g., a microprocessor, a microcontroller, an electronic controller, an electronic processor, or another suitable programmable device), a memory **140**, input units **145**, and output units **150**. The processing unit **135** includes, among other things, a control unit **155**, an arithmetic logic unit ("ALU") **160**, and a plurality of registers **165** (shown as a group of registers in FIG. **1**), and is implemented using a known computer architecture (e.g., a modified Harvard architecture, a von Neumann architecture, etc.). The processing unit **135**, the memory **140**, the input units **145**, and the output units **150**, as well as the various modules connected to the controller **105** are connected by one or more control and/or data buses (e.g., common bus **170**). The use of one or more control and/or data buses for the interconnection between and communication among the various modules and components would be known to a person skilled in the art in view of the embodiments described herein. The control and/or data buses are shown generally for illustrative purposes.

In some embodiments, the control system **100** also includes a camera **175** configured to detect the light from the modules **110**A-**110**C reflected off of the object **103** (as shown in FIG. **1**). In some embodiments, the camera **175** is a spectrometer, or another device specifically designed to detect a light spectrum. In other embodiments, the control system **100** does not include the camera **175** (as shown in FIG. **2**). In these embodiments, the control system **100** operates in an open loop manner (i.e., without a closed-loop camera feedback system).

The memory **140** is a non-transitory computer readable medium and includes, for example, a program storage area and a data storage area. The program storage area and the data storage area can include combinations of different types of memory, such as a ROM, a RAM (e.g., DRAM, SDRAM, etc.), EEPROM, flash memory, a hard disk, an SD card, or other suitable magnetic, optical, physical, or electronic memory devices. The processing unit **135** is connected to the memory **140** and executes software instructions that are capable of being stored in a RAM of the memory **140** (e.g., during execution), a ROM of the memory **140** (e.g., on a generally permanent basis), or another non-transitory computer readable medium such as another memory or a disc. Software included in the implementation of the control system **100** can be stored in the memory **140** of the controller **105**. The software includes, for example, firmware, one or more applications, program data, filters, rules, one or more program modules, and other executable instructions. The controller **105** is configured to retrieve from the memory **140** and execute, among other things, instructions related to the control processes and methods described herein. In other embodiments, the controller **105** includes additional, fewer, or different components.

The user interface **125** is included to control the control system **100**. The user interface **125** is operably coupled to the controller **105** to control, for example, the output of the light modules **110**A-**110**C, and generate and provide control signals for the driver circuits **115**A-**115**C. The user interface **125** can include any combination of digital and analog input devices to achieve a desired level of control for the control system **100**. For example, the user interface **125** can include a computer having a display and input devices, a touch-screen display, a plurality of knobs, dials, switches, buttons, faders, or the like. In some embodiments, the user interface **125** is separated from the control system **100** (e.g., as a portable device communicatively connected to the controller **105**).

The driver circuits **115**A-**115**C include a first driver circuit **115**A, a second driver circuit **115**B, and a third driver circuit **115**C that are operable to provide control signals to the light modules **110**A-**110**C. For example, the first driver circuit **115**A is connected to a first light module **110**A for providing one or more drive signals to an array of (i.e., one or more) light sources of the first light module **110**A. The second driver circuit **115**B is connected to a second light module **110**B for providing one or more drive signals to an array of (i.e., one or more) light sources on the second light module **110**B. The third driver circuit **115**C is connected to a third light module **110**C for providing one or more drive signals to an array of (i.e., one or more) light sources on the third light module **110**C. In some embodiments, each of the light modules **110**A-**110**C corresponds to a color channel of a light. In other embodiments, each of the light modules **110**A-**110**C corresponds to a separate light fixture.

The power control circuit **120** supplies a nominal AC or DC voltage to the control system **100**. In some embodiments, the power control circuit **120** is powered by one or more batteries or battery packs. In other embodiments, the power control circuit **120** is powered by mains power having nominal line voltages between, for example, 100V and 240V AC and frequencies of approximately 50-60 Hz. The power control circuit **120** is also configured to supply lower voltages to operate circuits and components within the control system **100**.

As illustrated in FIGS. **1** and **2**, the controller **105** is connected to light modules **110**A-**110**C. In some embodiments, each light module **110**A-**110**C is a chip-on-board ("COB") light source. A three light module embodiment is illustrated for exemplary purposes only. In other embodiments, four or more light modules are used to further enhance the system **100**'s ability to produce visible light. Conversely, in other implementations, fewer than three light modules are used (i.e., one or two light modules). In some embodiments, the light modules **110**A-**110**C are light emitting diode ("LED") light modules. In some embodiments, the light modules **110**A-**110**C produce white light. In other embodiments, the light modules **110**A-**110**C produce colored light (i.e., non-white light).

The control system **100** further includes a control interface **200** (see FIG. **3**) for controlling a visual appearance of the light output light from the light modules **110**A-**110**C that is, for example, reflected from the object **103**. In some embodiments, the control interface **200** is included in the user interface **125**. The control interface **200** is, for example, a graphical user interface ("GUI") that is displayed on a monitor or similar display. In some embodiments, the control interface **200** is a physical interface and includes one or more buttons, knobs, dials, faders, or the like.

The illustrated control interface **200** includes an optional enable parametric rendering adjustment section **205**, a first lighting effect level section **210**, and a second lighting effect level section **215**. The enable parametric rendering adjustment section **205** includes a YES checkbox **220** and a NO checkbox **225**. The checkboxes **220** and **225** are used to select or deselect parametric rendering adjustment (i.e., control based on visual appearance of the lighting effect).

The parametric rendering adjustment can use the first lighting effect level section **210** and/or the second lighting effect level section **215** to implement lighting effects that modify the appearance of light, for example, reflected off the object **103**. The first and second lighting effect level of the sections **210**, **215** may include control of quality, luminance, hue, power, color temperature, or the like. The first and second lighting effects are generic to any light fixture and allows the user to control effects to the best of the system's ability, regardless of what light fixture is used.

In some embodiments, the parametric rendering adjustment includes more than two lighting effect level sections. In the illustrated embodiment, each of the lighting effect level sections includes a maximum value and a minimum value. For the purposes of this embodiment, the maximum value is a value of positive 100 (e.g., oversaturation). The minimum value is a value of negative 100 (e.g., undersaturation). For example, the maximum undersaturation value is the inverse of the maximum oversaturation value. The first and second lighting effect level sections **210**, **215** each include a slider **230** and a drop-down menu **235**. The slider **230** ranges from negative 100 to positive 100 (e.g., from undersaturation to oversaturation). The drop-down menu **235** ranges from −100% to 100%. In other embodiments, the first and second lighting effect level sections **210** include different selection mechanisms. In conventional lighting control systems, the first and second lighting effects are not directly controllable along a continuum (i.e., negative 100 to positive 100). In this way, the control interface **200** permits the user to precisely control aspects of the output light that would not otherwise be directly adjustable and controllable by conventional controls, all while maintaining the same output chromaticity. Non-limiting examples of lighting effects to be controlled by the interface **200** are described in further detail herein.

With reference to FIGS. **4**-**8**C, in one embodiment, the lighting effect controlled by the interface **200** is the hue shift of an objected illuminated by the light output of the light arrays **110**A-**110**C. With this control, the illuminated object **103** may appear to an observer (i.e., a human or camera) to be different colors and can be adjusted by a user while holding the output light chromaticity constant.

With reference to FIG. **4**, a spectral reflectance function **300** of a first example object (e.g., a grapefruit) is illustrated. The spectral reflectance function **300** illustrates how incoming light will be reflected off the object—with longer wavelengths (e.g., greater than 600 nm) reflected more than shorter wavelengths. With the control interface **200**, the hue of the first example object may be controlled between a default condition, a positive hue shift condition (e.g., +100 adjustment of the first lighting effect level section **210**), and a negative hue shift condition (e.g., −100 adjustment of the first lighting effect level section **210**). In other words, the control interface **200** is utilized by a user to control the color appearance of the first example object without changing the chromaticity of the output light. For each of these conditions, the resulting spectral power distribution of light reflected off the first example object (i.e., the grapefruit's rendered spectra) is illustrated in FIG. **5**. Specifically, the rendered spectrum **305** is for the default condition, the rendered spectrum **310** is for the positive hue shift condition, and the rendered spectrum **315** for the negative hue shift condition.

With reference to FIG. **6**, each of these rendered spectrums **305**, **310**, **315** correspond to an object chromaticity **320**, **325**, **330** as illustrated in a CIE 1931 chromaticity diagram. More specifically, the first example object appears to an observer at a default chromaticity **320** with an output light chromaticity **318**. In the illustrated embodiment, the output light chromaticity **318** is on the Planckian locus **319** and is held constant. The first example object appears to an observer at a positive hue shift chromaticity **325** in the positive hue shift condition and at a negative hue shift chromaticity **330** in the negative hue shift condition. As such, the control interface **200** permits a user to adjust the chromaticity of the light reflected off of the first example object while maintaining the output light chromaticity constant.

With reference to FIGS. **7**A-**7**C, color vector graphics are illustrated according to the TM-30 standard. In general, a color vector graphic shows how the color evaluation samples, representative of a wide range of objects, are likely to undergo either a saturation (chroma) shift, a hue shift, or both. The color vector graphic is divided into 16 equal sections with for, example, section 1 representative of red and section 9 representative of cyan. The reference illuminant is normalized to a reference circle **350** and the gamut of the light source is plotted relative to the circle as a distorted circle (e.g., **360** of FIG. **7**B). Arrows that point radially into the reference circle **350** indicate areas of decreased saturation while areas that point radially out of the reference circle **350** indicate areas of increased saturation. Arrows that do not point directly to the center of the circle **350** or directly away from the center **350** of the circle are representing hue shift. In short, the color vector graphics can be used to illustrate how objects will appear in an output light relative to a reference light source (e.g., daylight).

With continued reference to FIGS. **7**A-**7**C, the color vector graphics are illustrated for the default condition (FIG. **7**A), the positive hue shift condition (FIG. **7**B), and the negative hue shift condition (FIG. **7**C). In FIG. **7**A, the light source output gamut **355** closely tracks the reference circle **350** in the default condition. Attributes of the output light (R_f, R_g, CCT, D_{uv}) in the default condition are also listed in FIG. **7**A. In FIG. **7**B, the light source output gamut **360** is adjusted in the positive hue shift condition, and in FIG. **7**C, the light source output gamut **365** is adjusted in the negative hue shift condition. The CCT value of 3200 K and D_{uv} of 0.0000 is held constant for FIGS. **7**A-**7**C.

To achieve the default, positive hue shift, and negative hue shift conditions desired by the user, the controller **105** determines the corresponding target output light spectrums **370**, **380**, **390** illustrated in FIGS. **8**A-**8**C. The target output light spectrums **370**, **380**, **390** correspond to the default, positive hue shift, and negative hue shift conditions, respectively, and may be determined by selecting one of the many possible metamers for the target chromaticity (e.g., **318**). In other words, there are numerous metamers for the target chromaticity (e.g., **318**) and the controller **105** selects the metamer that results in the hue shift condition desired by the user. The selection of the metamer for a desired hue shift may be preprogrammed into the memory **140** as a look-up table, for example. In other embodiments, the metamer could also be calculated by methods including, but not limited to, live calculation within the luminaire, live calculation within the controller, stored spectrum, spectrum measured live using a suitable sensor, chromaticity point measured live using a suitable sensor, further input from the user, learned behavior based on a user's previous selections, learned behavior based on a user's stored preferences, or combinations thereof.

With the target output light spectrums **370**, **380**, **390** determined, conventional spectral matching techniques (such as those disclosed in U.S. Pat. No. 6,683,423; incorporated herein) are utilized to determine how to drive the actual light emitters contained within a given fixture. In other words, the control system **100** determines an idealized target output spectrum for controlling the hue shift of the first example object. As one example, the actual output spectral power distribution achieved for an example light fixture containing eight primary emitters is illustrated as output spectrum distributions **375**, **385**, **395** on FIGS. **8**A-**8**C. In other words, the output spectrum distributions **375**, **385**, **395** illustrate a given light fixture's best ability to match the target output light spectrums **370**, **380**, **390**.

In summary, FIGS. **4**-**8**C illustrate the implementation of control for hue shift of a first example object illuminated by a light fixture (i.e., an example light effect level). With the control interface **200**, a user adjusts the light that is reflected off of the first example object (i.e., change in reflected light chromaticities **320**, **325**, **330**), while holding the output light chromaticity constant (e.g., chromaticity **318**). The hue shift of the first example object is not directly adjustable with conventional controls.

With reference to FIGS. **9**-**11**C, in another embodiment, the lighting effect controlled by the interface **200** is the chroma shift of an object illuminated by the light output of the light arrays **110**A-**110**C. With this control, the illuminated object **103** may appear to an observer (i.e., a human or camera) to be different saturations and can be adjusted by a user while holding the output light chromaticity constant.

With reference to FIG. **9**, a spectral reflectance function **400** of a second example object (e.g., one example of human skin) is illustrated. The spectral reflectance function **400** illustrates how incoming light will be reflected off the second example object. With the control interface **200**, the chroma (i.e., saturation) of the second example object may be controlled between a default condition, a positive chroma shift condition (e.g., +100 adjustment of the first lighting effect level section **210**), and a negative chroma shift condition (e.g., −100 adjustment of the first lighting effect level section **210**). In other words, the control interface **200** is utilized by a user to control the saturation appearance of the second example object without changing the chromaticity of the output light. As such, the R_g value of the output light is adjusted to be greater than or less than 100.

With reference to FIGS. **10**A-**10**C, the color vector graphics are illustrated for the default condition (FIG. **10**A), the positive chroma shift condition (FIG. **10**B), and the negative chroma shift condition (FIG. **10**C). In FIG. **10**A, the light source output gamut **405** closely tracks the reference circle **402** in the default condition and the R_g value is 100. Attributes of the output light (R_f, CCT, D_{uv}) in the default condition are also listed in FIG. **10**A. In FIG. **10**B, the light source output gamut **410** is adjusted in the positive chroma shift condition with a R_g value of 106, and in FIG. **10**C, the light source output gamut **415** is adjusted in the negative chroma shift condition with a R_g value of 90. The CCT value of 4000 K and D_{uv} of 0.0000 is held constant for FIGS. **10**A-**10**C.

With reference to FIGS. **11**A-**11**C, for each of the desired chroma-shifts in the second example object there is a corresponding output target spectrum power distribution **420**, **425**, **430**. The target output light spectrums **420**, **425**, **430** correspond to the default, positive chroma shift, and negative chroma shift conditions, respectively, and may be determined by selecting one of the many possible metamers for the target chromaticity (e.g., CCT=4000 K and D_{uv}=0.0000). In other words, there are numerous metamers for the target chromaticity and the controller **105** selects the metamer that results in the chroma shift condition for the second example object desired by the user. The selection of the metamer for a desired chroma shift may be preprogrammed into the memory **140** as a look-up table, for example. In other embodiments, the metamer could also be calculated by methods including, but not limited to, live calculation within the luminaire, live calculation within the controller, stored spectrum, spectrum measured live using a suitable sensor, chromaticity point measured live using a suitable sensor, further input from the user, learned behavior based on a user's previous selections, learned behavior based on a user's stored preferences, or combinations thereof. The target output light spectrums **420**, **425**, **430** are generalized targets (similar to the target spectrum **370**, **380**, **390**) that are applicable to any type of light fixture being used. Conventional target spectral matching techniques may be utilized to drive emitters in a given light fixture in order to approximate the target.

In summary, FIGS. **9**-**11**C illustrate the implementation of control for chroma shift of a second example object illuminated by a light fixture (i.e., an example light effect level). With the control interface **200**, a user adjusts the saturation of the light reflected off of the second example object, while holding the output light chromaticity constant. The chroma shift of the second example object is not directly adjustable with conventional controls.

With reference to FIGS. **12**A-**13**C, in another embodiment, the lighting effect controlled by the interface **200** is the generalized saturation appearance of object(s) (i.e., R_g value) of an approximately 5600 K light output of the light arrays **110**A-**110**C. With the control interface **200**, the generalized saturation may be controlled between a default condition, a generalized oversaturated condition (e.g., +100 adjustment of the first lighting effect level section **210**), and a generalized undersaturation condition (e.g., −100 adjustment of the first lighting effect level section **210**). In other words, the control interface **200** is utilized by a user to control the generalized saturation appearance of object(s) without changing the chromaticity of the output light. As such, the R_g value of the output light is adjusted to be greater than or less than 100.

With reference to FIGS. **12**A-**12**C, the color vector graphics are illustrated for the default condition (FIG. **12**A), the generalized oversaturation condition (FIG. **12**B), and the generalized undersaturation condition (FIG. **12**C). In FIG. **12**A, the light source output gamut **505** closely tracks the reference circle **502** in the default condition and the R_g value is 100. Attributes of the output light (R_f, CCT, D_{uv}) in the default condition are also listed in FIG. **12**A. In FIG. **12**B, the light source output gamut **510** is adjusted in the generalized oversaturation condition with a R_g value of 110, and in FIG. **12**C, the light source output gamut **515** is adjusted in the generalized undersaturation condition with a R_g value of 91. The CCT value of 5599 K and D_{uv} of 0.0032 is held constant for FIGS. **12**A-**12**C.

With reference to FIGS. **13**A-**13**C, for each of the desired generalized saturation levels there is a corresponding output target spectrum power distribution **520**, **525**, **530**. The target output light spectrums **520**, **525**, **530** correspond to the default, oversaturated, and undersaturated conditions, respectively, and may be determined by selecting one of the many possible metamers for the target chromaticity (e.g., CCT=5599 K and D_{uv}=0.0032). In other words, there are numerous metamers for the target chromaticity and the controller **105** selects the metamer that results in the generalized saturation level desired by the user. The selection of the metamer for a desired saturation level may be preprogrammed into the memory **140** as a look-up table, for example. In other embodiments, the metamer could also be calculated by methods including, but not limited to, live calculation within the luminaire, live calculation within the controller, stored spectrum, spectrum measured live using a suitable sensor, chromaticity point measured live using a suitable sensor, further input from the user, learned behavior based on a user's previous selections, learned behavior based on a user's stored preferences, or combinations thereof. The target output light spectrums **520**, **525**, **530** are generalized targets (similar to the target spectrum **370**, **380**, **390**) that are applicable to any type of light fixture being used.

In summary, FIGS. **12**A-**13**C illustrate the implementation of control for generalized saturation appearance of object(s) in an approximately 5600K illuminant (i.e., an example light effect level), while holding the output light chromaticity constant. The generalized saturation of a 5600K illuminant is not directly adjustable with conventional controls.

With reference to FIGS. **14-16**, in another embodiment, the lighting effect controlled by the interface **200** is the relative luminance of an object illuminated by a non-white light output of the light arrays **110**A-**110**C. With this control, the illuminated object **103** may appear to an observer (i.e., a human or camera) to be brighter or darker and can be adjusted by a user while holding the output light chromaticity constant at a non-white color and equal luminous flux.

With reference to FIG. **14**, a spectral reflectance function **600** of a third example object (e.g., a purple scarf) is illustrated. The spectral reflectance function **600** illustrates how incoming light will be reflected off the third example object. With the control interface **200**, the luminance (i.e., brightness) of the third example object may be controlled between a default condition (point **605** in FIG. **16**), an increased relative luminance condition (point **610** in FIG. **16**) (e.g., +100 adjustment of the first lighting effect level section **210**), and a decreased relative luminance condition (point **615** in FIG. **16**) (e.g., −100 adjustment of the first lighting effect level section **210**). The minimum (e.g., −100 from the interface **200** of FIG. **3**) and maximum (e.g., +100 from the interface **200** of FIG. **3**) are defined as the extremes of the lighting effect adjustment. The changes that occur to the target output spectrum between the spectrums **625**, **630** for the minimum and maximum control levels, respectively, can then be mapped (e.g., linearly) to produce a target spectrum for control values between −100 and 100 for a controllable lighting effect. In other words, the control interface **200** is utilized by a user to control the luminance of the third example object without changing the chromaticity of the output light—which in this example is a blue output light. The brightness of the third example object is being adjusted relative to the rest of the scene illuminated, since the luminous flux of the output light is held constant.

With reference to FIGS. **15**A-**15**C, for each of the desired relative brightnesses of the third example object there is a corresponding output target spectrum power distribution **620**, **625**, **630**. The target output light spectrums **620**, **625**, **630** correspond to the default, increased relative brightness, and decreased relative brightness conditions, respectively, and may be determined by selecting one of the many possible metamers for the target chromaticity (e.g., blue, or "steel blue"). In other words, there are numerous metamers for the target chromaticity and the controller **105** selects the metamer that results in the relative brightness condition for the third example object desired by the user. The selection of the metamer for a desired relative luminance may be preprogrammed into the memory **140** as a look-up table, for example. The target output light spectrums **620**, **625**, **630** are generalized targets (similar to the target spectrums **370**, **380**, **390**) that are applicable to any type of light fixture being used.

Although the described embodiment uses a look-up table to calculate a metamer, in other embodiments, the metamer could also be calculated by methods including, but not limited to, live calculation within the luminaire, live calculation within the controller, stored spectrum, spectrum measured live using a suitable sensor, chromaticity point measured live using a suitable sensor, further input from the user, learned behavior based on a user's previous selections, learned behavior based on a user's stored preferences, or combinations thereof.

In summary, FIGS. **14-16** illustrate the implementation of control for relative brightness of a third example object illuminated by a light fixture (i.e., an example light effect level). With the control interface **200**, a user adjusts the luminance of the light reflected off of the third example object relative to its surroundings, while holding the output light chromaticity constant at a non-white color and equal luminous flux. The relative luminance of the third example object illuminated by non-white light is not directly adjustable with conventional controls.

FIG. **17** illustrates a method **700** for using the control system **100** to adjust a lighting effect of the output light from light arrays **110**A-**110**C. Various steps described herein with respect to the process **700** are capable of being executed simultaneously, in parallel, or in an order that differs from the illustrated serial manner of execution.

In some embodiments, the user enables the parametric rendering adjustment and alters the first lighting effect level **210** and/or the second lighting effect level **215** on the control interface **200** (see FIG. **3**) to control the visual appearance of light on the object **103** (STEP **705**). In other embodiments, enabling parametric rendering adjustment is not specifically required. Before any adjustments are made, the method **700** includes energizing the light fixture to produce a first light output with a first chromaticity and a first spectral power distribution (STEP **710**). In other words, the light fixture generates a default light output. The controller **105** receives signals related to a user input that is representative of a desired adjustment of a lighting effect (STEP **715**). The desired adjustment of a lighting effect may include adjustment of the Illumination Engineering Society ("IES") Technical Memorandum 30 ("TM-30") R_g value of the light output; adjustment of a hue shift in an object illuminated by the light output; or adjustment of a chroma shift in an object illuminated by the light output. In other embodiments, the desired adjustment of a lighting effect may include adjustment of one or more parameters or metrics of a light output including but not limited to; Television Lighting Consistency Index ("TLCI"); Color Rendering Index ("CRI") R_a; CRI R9; Spectral Similarity Index ("SSI"); TM-30 R_f; TM-30 R_g; TM-30 $R_{cs,h1}$; TB-30 $R_{f,h1}$; TM-30 Annex E's PVF (Preference, Vividness, Fidelity) values; Color Quality

Scale ("CQS"); Pigment/dye/colorant alignment; Skin tone quality; Vibrance/richness; Increase or decrease in fluorescence or excitation of optical brighteners; generalized Cool/Warm appearance shift; Light source selection (e.g., tungsten 3200K vs HID 3200K vs fluorescent 3200K). Such adjustments may be applied independently or simultaneously in any combination of multiple parameters. In other embodiments, the desired adjustment of a lighting effect includes adjustment of a relative luminance of an object illuminated by the light output. In a further embodiment the desired adjustment of a lighting effect is to adjust skin tone rendition by suppressing or enhancing the cyan wavelengths. This adjustment, while maintaining a chromaticity match or constant chromaticity, provides the user the ability to tune the appearance of skin tones both to the eye and to a camera.

The method **700** further includes generating a target output light spectrum based on the user input received (STEP **720**). In some embodiments, the target spectrum is retrieved from a look-up table stored in the memory **140**. In other embodiments, the metamer could also be calculated by methods including, but not limited to, live calculation within the luminaire, live calculation within the controller, stored spectrum, spectrum measured live using a suitable sensor, chromaticity point measured live using a suitable sensor, further input from the user, learned behavior based on a user's previous selections, learned behavior based on a user's stored preferences, or combinations thereof. The method **700** includes energizing the light fixture to produce a second light output with the first chromaticity and a second spectral power distribution (STEP **725**). The second spectral power distribution approximates or matches the target spectrum and will depend on the type of light fixture utilized to create the target spectrum.

The inputted first and/or second lighting effect levels **210**, **215** are used to modify a spectrum of light produced by the light modules **110**A-**110**C. If the appearance of the object **103** is not satisfactory, the user can modify the first lighting effect level **210** and/or the second lighting effect level **215** on the control interface **200**. In this way, the control is open-loop and based on user observations and adjustments. As such, the controller **105** is configured to dynamically alter the light output to achieve a desired visual appearance of the object **103**, for example. In some embodiments, the light projected onto the object **103** can be white light or colored light (i.e., light other than white light), as shown in FIGS. **14-16**.

In some embodiments, the camera **175** can be used to detect a reflectance of the light off of the object **103** (STEP **730**). Based on the reflectance of light off of the object **103**, as detected by the camera **175**, further adjustments to the target output light spectrum may be made. In this sense, the control may provide a closed-loop system that detects and measures the lighting effect being adjusted. In some embodiments, STEP **730** is not included.

Thus, embodiments described herein provide, among other things, systems, methods, and devices for controlling a light output based on a visual appearance of one or more objects. Various features and advantages are set forth in the following claims.

What is claimed is:

1. A method for control of a light fixture, the method comprising:

energizing the light fixture to produce a first light output with a first chromaticity and a first spectral power distribution;

receiving a user input representative of a desired adjustment of a lighting effect;

generating a target spectrum based on the user input; and

energizing the light fixture to produce a second light output with the first chromaticity and a second spectral power distribution, the second power distribution approximates the target spectrum.

2. The method of claim **1**, wherein the lighting effect is the TM-30 R_g value of the light output.

3. The method of claim **1**, wherein the lighting effect is a hue shift of the light reflected by an object illuminated by the light output.

4. The method of claim **1**, wherein the lighting effect is a chroma shift of the light reflected by an object illuminated by the light output.

5. The method of claim **1**, wherein the lighting effect is a Television Lighting Consistency Index ("TLCI") value of the light output.

6. The method of claim **1**, wherein the lighting effect is a Color Rendering Index ("CRI") Ra value of the light output.

7. The method of claim **1**, wherein the lighting effect is a Spectral Similarity Index ("SSI") value of the light output.

8. The method of claim **1**, wherein the lighting effect is the relative luminance of an object illuminated by the light output.

9. The method of claim **1**, wherein the first light has a first lumen output and the second light has a second lumen output equal to the first lumen output.

10. The method of claim **1**, wherein the first chromaticity is matched for a human eye observer.

11. The method of claim **1**, wherein the first chromaticity is matched for a camera observer.

12. The method of claim **1**, further including detecting reflected light off an object positioned in the second light output with a camera and adjusting the target spectrum based on the detected reflected light.

13. The method of claim **1**, wherein the first chromaticity is non-white color.

14. The method of claim **1**, wherein generating the target spectrum based on the user input includes retrieving the target spectrum from a table stored in a memory.

15. The method of claim **1**, wherein the lighting effect is the TM-30 R_f value of the light output.

16. The method of claim **1**, wherein the lighting effect is the TM-30 $R_{cs,h1}$ value of the light output.

17. The method of claim **1**, wherein the lighting effect is the TM-30 $R_{f,\,h1}$ value of the light output.

18. A lighting control system comprising:

one or more light fixtures;

one or more driver circuits configured to provide drive signals to the one or more light fixtures;

a user interface configured to receive an input related to a light output of the one or more light fixtures, the input being representative of an adjustment of a lighting effect; and

a controller connected to the one or more driving circuits and the user interface, the controller including a processor and a memory, the controller configured to:

energize the one or more light fixtures to produce a first light output with a first chromaticity and a first spectral power distribution,

receive the input representative of the adjustment of the lighting effect,

generate a target spectrum based on the input, and

energize the one or more light fixtures to produce a second light output with the first chromaticity and a second spectral power distribution, the second power distribution approximates the target spectrum.

19. The lighting control system of claim **18**, wherein the first chromaticity is a non-white color.

20. A controller for controlling a light output of a light fixture, the controller including a non-transitory computer readable medium and a processor, the controller including computer executable instructions stored in the computer readable medium for controlling operation of the controller to:

energize the light fixture to produce a first light output with a first chromaticity and a first spectral power distribution;

receive an input representative of an adjustment of a lighting effect;

generate a target spectrum based on the user input; and

energize the light fixture to produce a second light output with the first chromaticity and a second spectral power distribution, the second power distribution approximates the target spectrum.

* * * * *

Exhibit C

US011849519B2

(12) **United States Patent**
Florac et al.

(10) **Patent No.: US 11,849,519 B2**
(45) **Date of Patent: *Dec. 19, 2023**

(54) **SYSTEMS, METHODS, AND DEVICES FOR INFLUENCING SPECTRAL CONTENT OF A LIGHT OUTPUT**

(71) Applicant: **Electronic Theatre Controls, Inc.**, Middleton, WI (US)

(72) Inventors: **William R. Florac**, Verona, WI (US); **Evan Gnam**, Madison, WI (US); **Wendy Luedtke**, Brooklyn, NY (US); **James Uphoff**, Madison, WI (US)

(73) Assignee: **Electronic Theatre Controls, Inc.**, Middleton, WI (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 42 days.

This patent is subject to a terminal disclaimer.

(21) Appl. No.: **17/583,765**

(22) Filed: **Jan. 25, 2022**

(65) **Prior Publication Data**

US 2022/0151044 A1 May 12, 2022

Related U.S. Application Data

(63) Continuation of application No. 17/173,286, filed on Feb. 11, 2021, now Pat. No. 11,240,898.

(60) Provisional application No. 62/975,459, filed on Feb. 12, 2020.

(51) **Int. Cl.**

H05B 47/11	(2020.01)
H05B 45/20	(2020.01)
H05B 47/125	(2020.01)
H05B 45/22	(2020.01)
H05B 47/14	(2020.01)

(52) **U.S. Cl.**
CPC ***H05B 47/11*** (2020.01); ***H05B 45/20*** (2020.01); ***H05B 45/22*** (2020.01); ***H05B 47/125*** (2020.01); ***H05B 47/14*** (2020.01)

(58) **Field of Classification Search**
CPC H05B 47/11; H05B 47/14; H05B 47/125; H05B 45/20; H05B 45/22; H05B 39/04; Y02B 20/40
See application file for complete search history.

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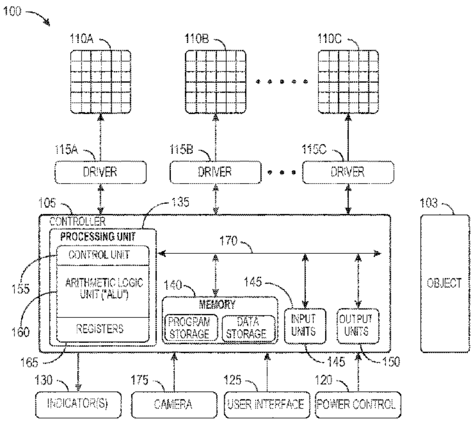
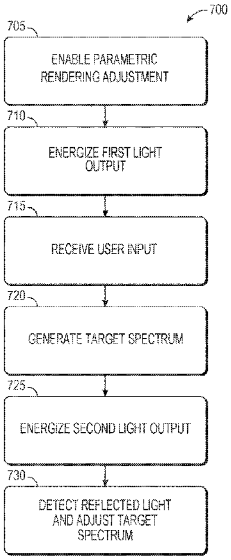
Primary Examiner — Haissa Philogene
(74) *Attorney, Agent, or Firm* — Michael Best & Friedrich LLP

(57) **ABSTRACT**

A method for control of a light fixture, the method including energizing the light fixture to produce a first light output with a first chromaticity and a first spectral power distribution, receiving a user input representative of a desired adjustment of a lighting effect, generating a target spectrum based on the user input, and energizing the light fixture to produce a second light output with the first chromaticity and a second spectral power distribution. The second power distribution approximates the target spectrum.

20 Claims, 10 Drawing Sheets





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2022/0110195	A1 *	4/2022	Casey	H05B 47/155

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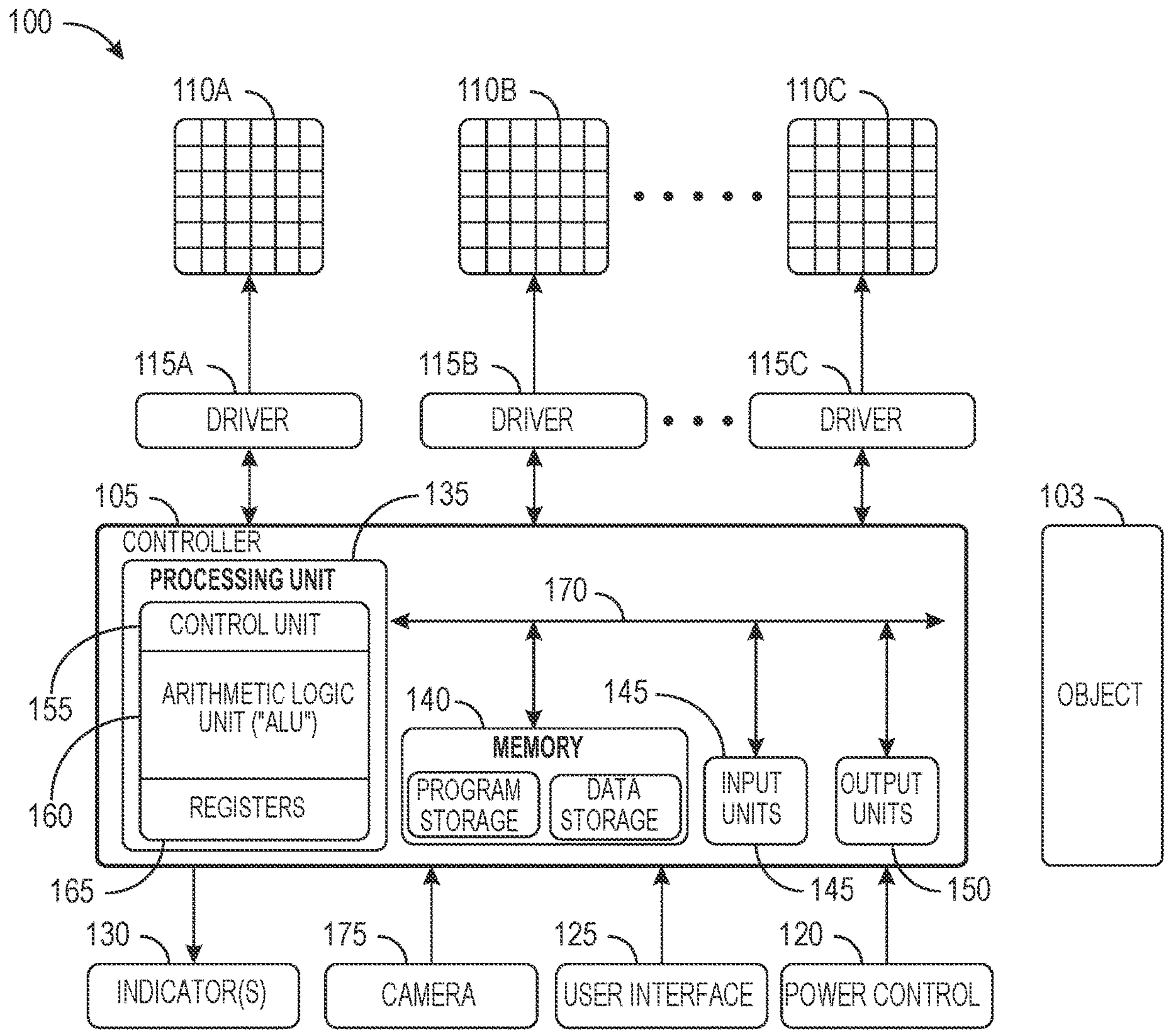

100
110A
110B
110C
115A
115B
115C
DRIVER
DRIVER
DRIVER
105
135
103
CONTROLLER
PROCESSING UNIT
CONTROL UNIT
ARITHMETIC LOGIC UNIT ("ALU")
REGISTERS
170
140
145
MEMORY
PROGRAM STORAGE
DATA STORAGE
INPUT UNITS
OUTPUT UNITS
OBJECT
155
160
165
145
150
130
175
125
120
INDICATOR(S)
CAMERA
USER INTERFACE
POWER CONTROL

FIG. 1

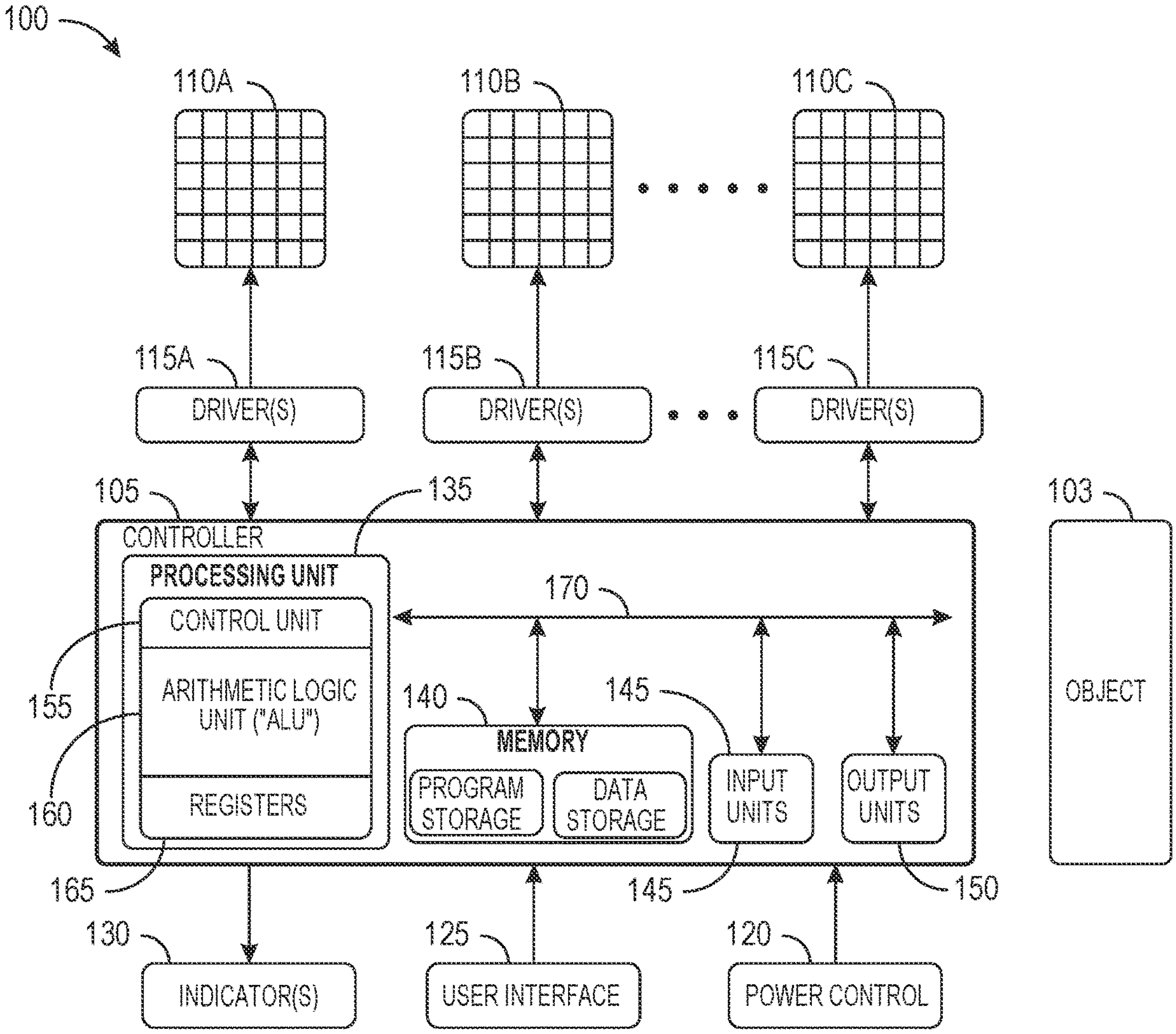

100
110A
110B
110C
115A
115B
115C
DRIVER(S)
DRIVER(S)
DRIVER(S)
105
135
103
CONTROLLER
PROCESSING UNIT
CONTROL UNIT
ARITHMETIC LOGIC UNIT ("ALU")
REGISTERS
170
140
145
MEMORY
PROGRAM STORAGE
DATA STORAGE
INPUT UNITS
OUTPUT UNITS
OBJECT
155
160
165
145
150
130
125
120
INDICATOR(S)
USER INTERFACE
POWER CONTROL

FIG. 2

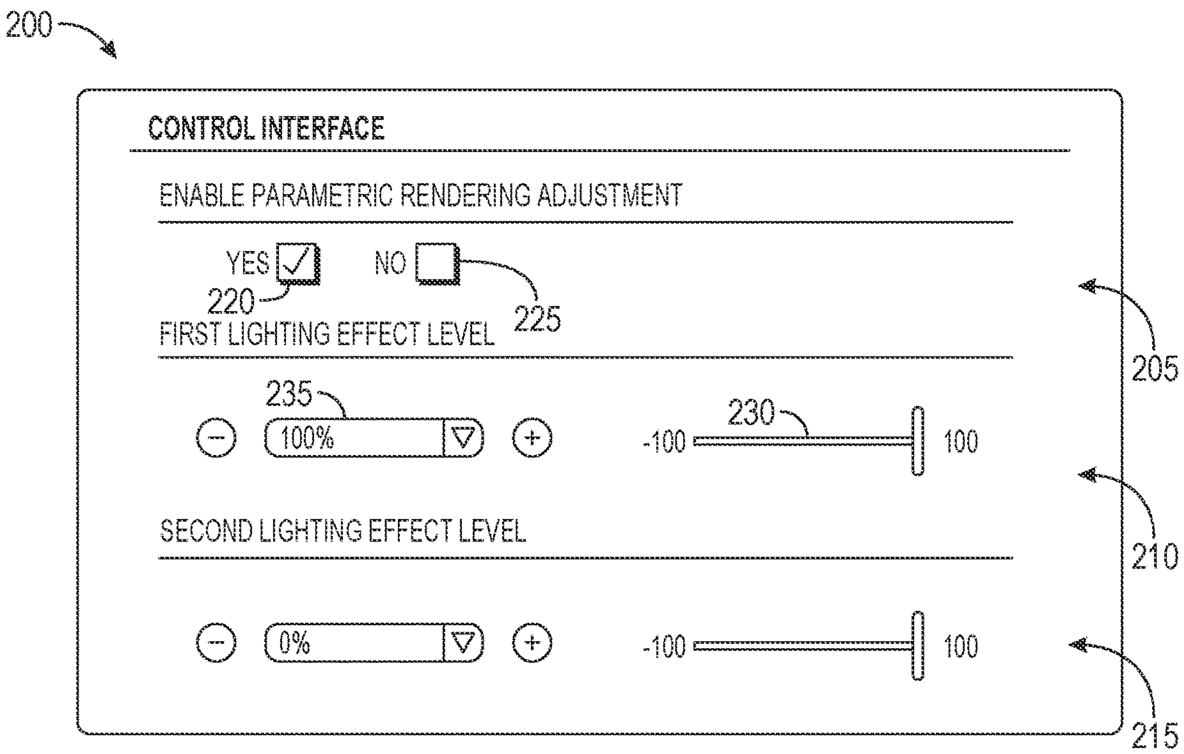

200
CONTROL INTERFACE
ENABLE PARAMETRIC RENDERING ADJUSTMENT
YES ☑
NO ☐
220
225
FIRST LIGHTING EFFECT LEVEL
235
100%
230
-100
100
SECOND LIGHTING EFFECT LEVEL
0%
-100
100
205
210
215

FIG. 3

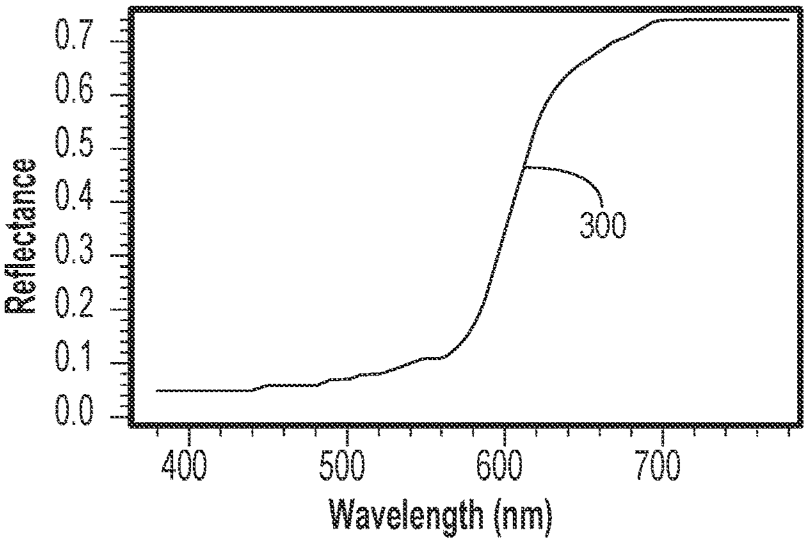

0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Reflectance
300
400
500
600
700
Wavelength (nm)

FIG. 4

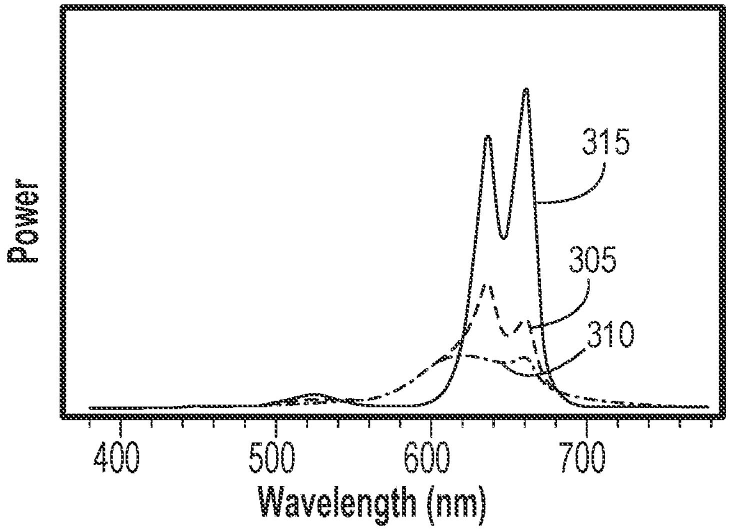

Power
315
305
310
400
500
600
700
Wavelength (nm)

FIG. 5

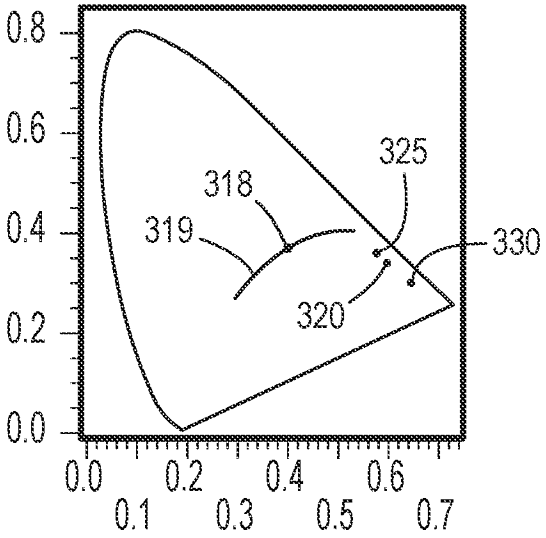

0.8
0.6
0.4
0.2
0.0
325
318
319
330
320
0.0
0.2
0.4
0.6
0.1
0.3
0.5
0.7

FIG. 6

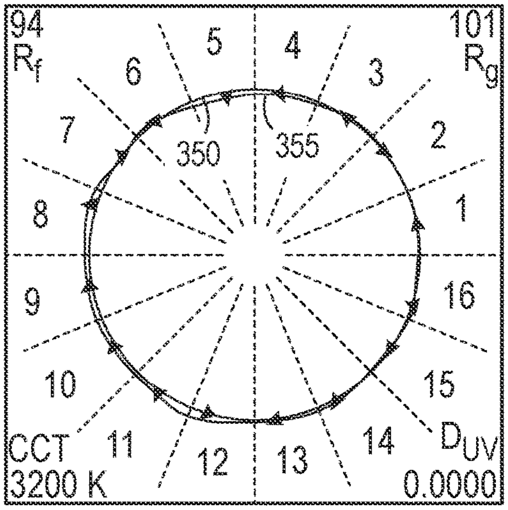


FIG. 7A

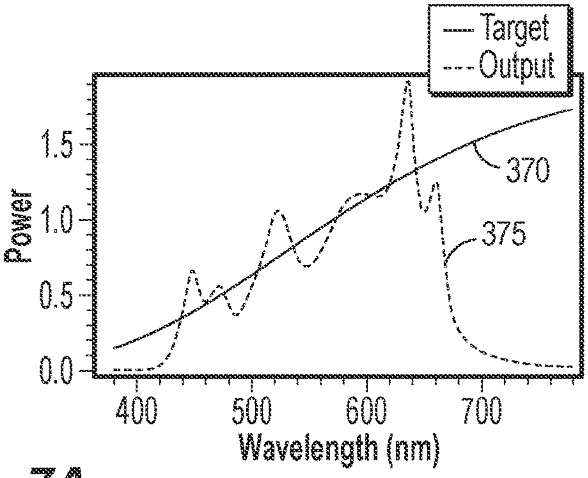


FIG. 8A

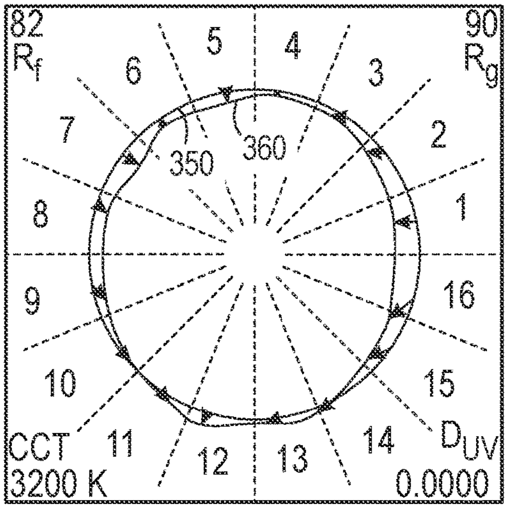


FIG. 7B

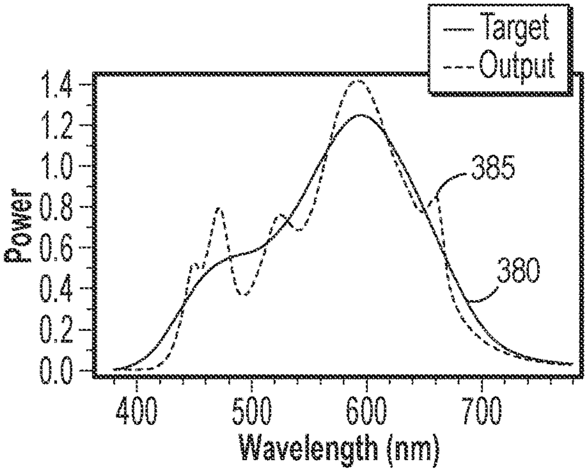


FIG. 8B

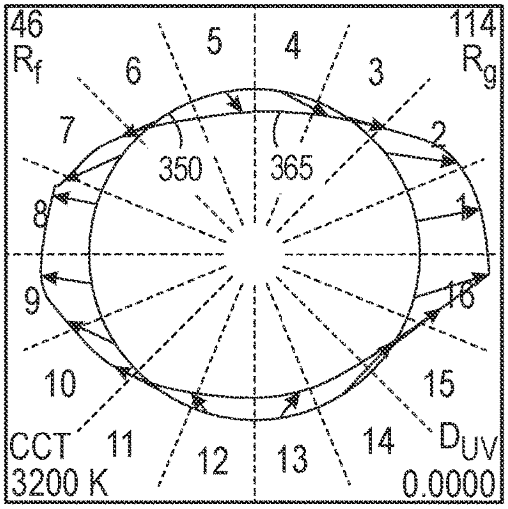


FIG. 7C

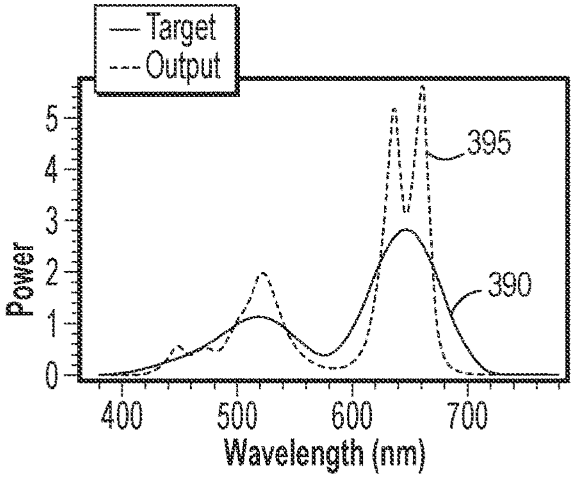
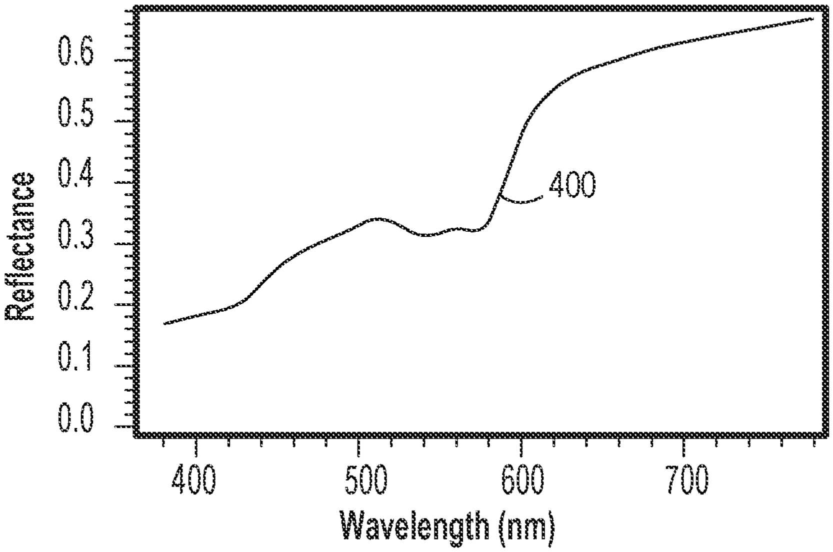


FIG. 8C



Reflectance
0.6
0.5
0.4
0.3
0.2
0.1
0.0
400
400
500
600
700
Wavelength (nm)

FIG. 9

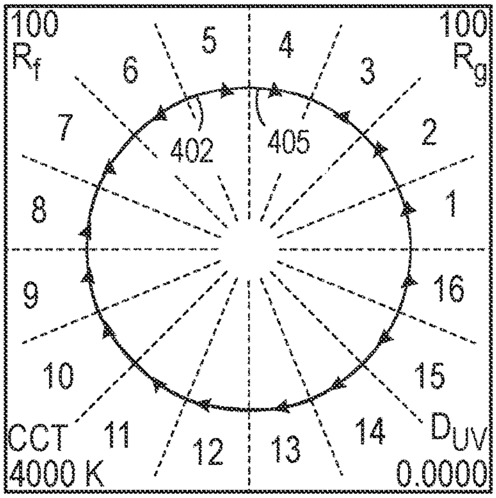


FIG. 10A

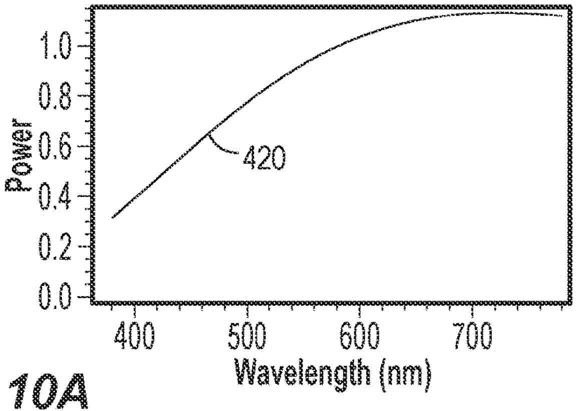


FIG. 11A

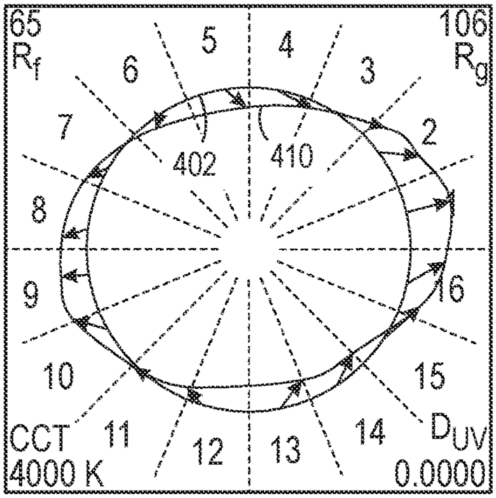


FIG. 10B

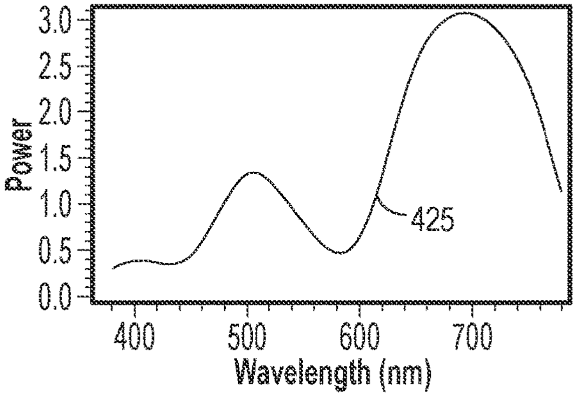


FIG. 11B

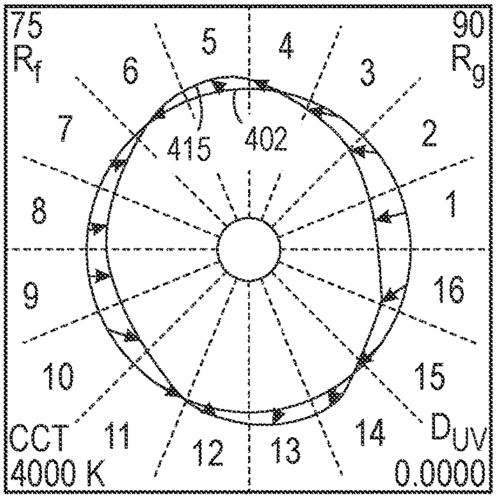


FIG. 10C

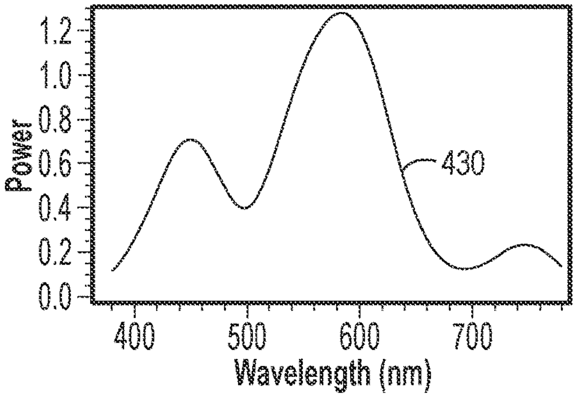


FIG. 11C

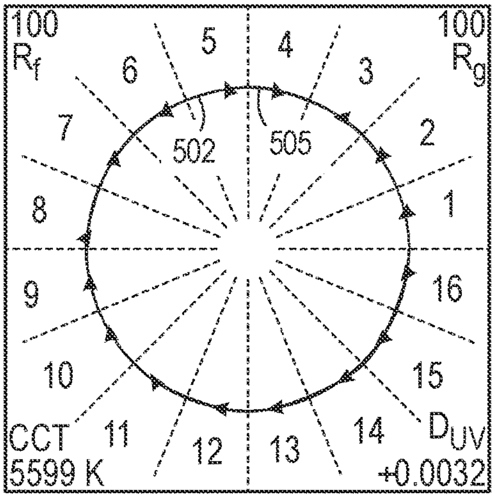


FIG. 12A

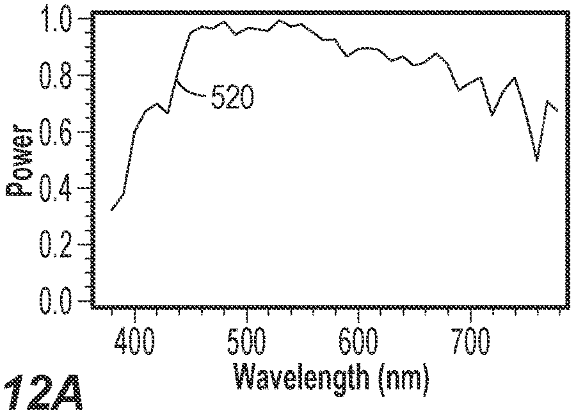


FIG. 13A

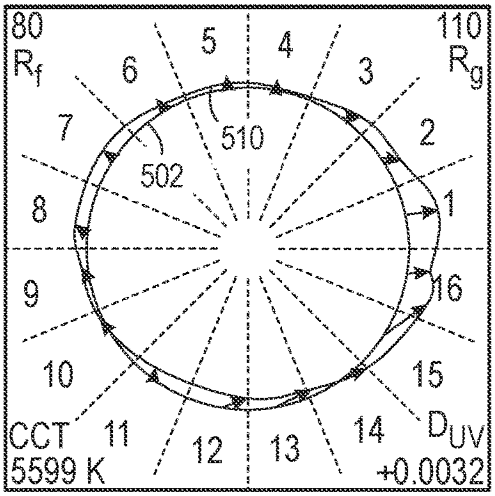


FIG. 12B

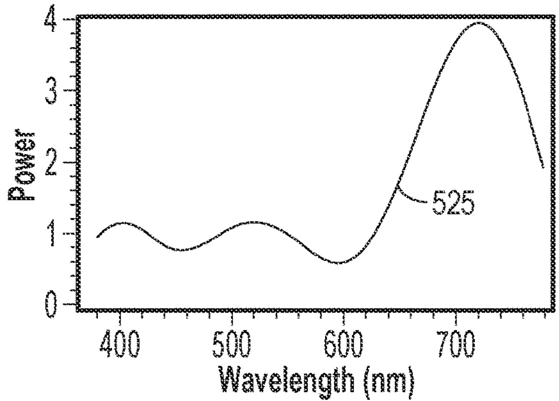


FIG. 13B

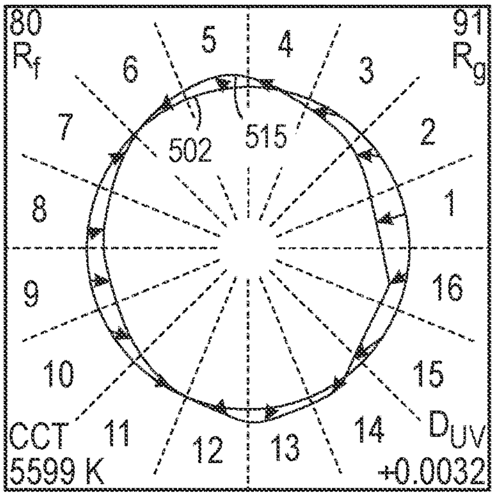


FIG. 12C

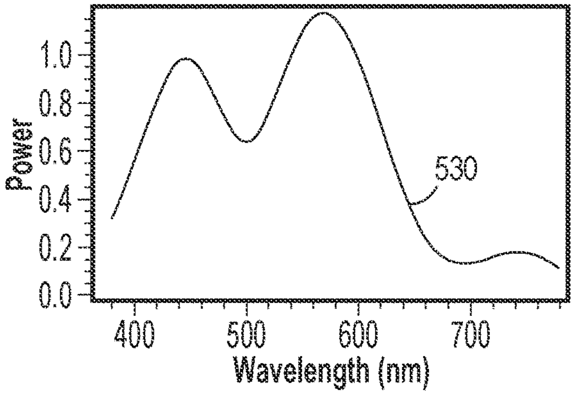


FIG. 13C

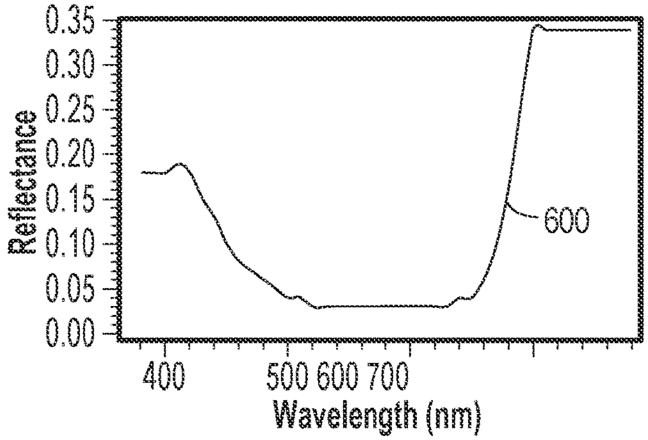


FIG. 14

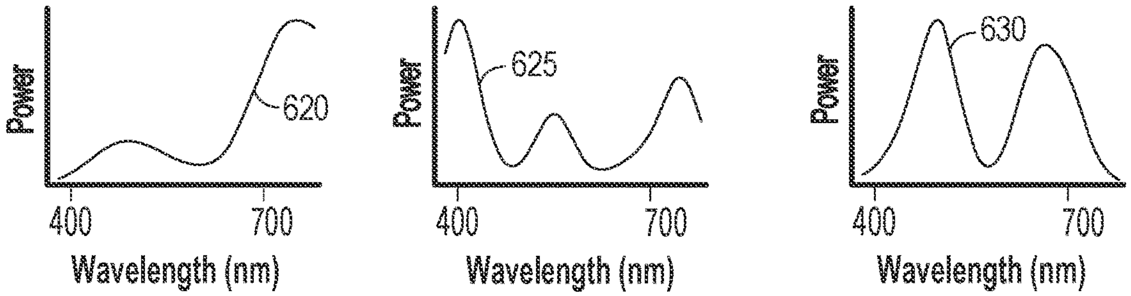


FIG. 15A FIG. 15B FIG. 15C

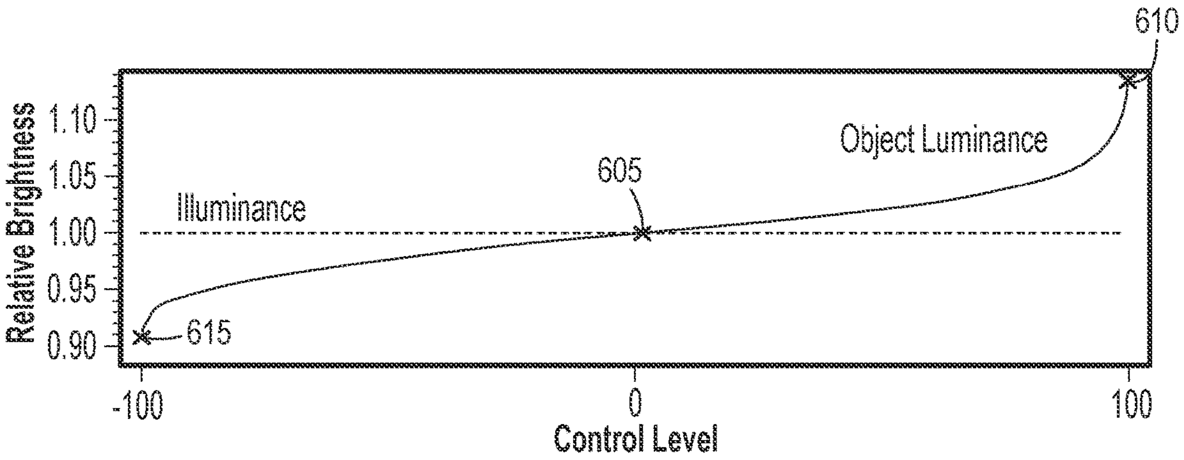


FIG. 16

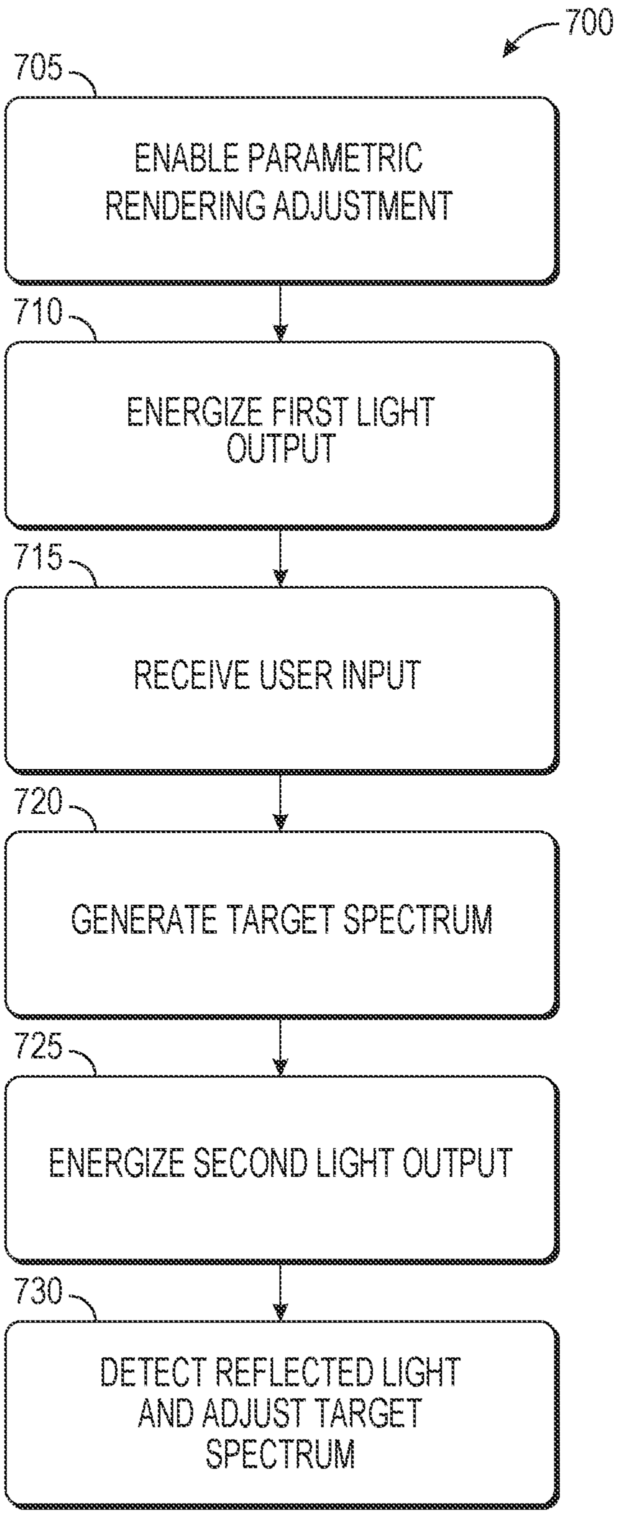

700
705
ENABLE PARAMETRIC RENDERING ADJUSTMENT
710
ENERGIZE FIRST LIGHT OUTPUT
715
RECEIVE USER INPUT
720
GENERATE TARGET SPECTRUM
725
ENERGIZE SECOND LIGHT OUTPUT
730
DETECT REFLECTED LIGHT AND ADJUST TARGET SPECTRUM

FIG. 17

SYSTEMS, METHODS, AND DEVICES FOR INFLUENCING SPECTRAL CONTENT OF A LIGHT OUTPUT

CROSS-REFERENCE TO RELATED APPLICATIONS

This application is a continuation of U.S. patent application Ser. No. 17/173,286, filed Feb. 11, 2021, which claims the benefit of U.S. Provisional Patent Application No. 62/975,459, filed Feb. 12, 2020, the entire content of each of which is hereby incorporated by reference.

FIELD

Embodiments described herein relate to influencing the spectral content of a light output.

BACKGROUND

Lighting systems used in architecture, theaters, concert stages, and other applications may be configured to control the light produced by a light source, such as a light fixture, luminaire, array of light emitting diodes, or other lighting device.

SUMMARY

The lighting system may be controlled in various ways to produce a desired chromaticity (i.e., color) for the output light. Holding the chromaticity of the light output while adjusting the spectral content of the light output is called metameric control. For example, U.S. Pat. No. 8,723,450, incorporated herein by reference, discloses controlling the spectral content of the output of a light fixture by modifying the output intensity value of one or more of the light sources that make up the light fixture. For example, the user may adjust upwards the power output of a red light emitting diode ("LED") within the light fixture. After modifying the output intensity values of individual emitters, a color control and matching technique is used to identify a new set of output intensity values for the remaining emitters that maintains the desired color output. The method of adjusting spectral content of a light output disclosed in U.S. Pat. No. 8,723,450 is specific to a given light fixture because the control adjusts the output of the specific light sources (e.g., individual LED) contained within the light fixture. However, different light fixtures have different light sources, so the method disclosed in U.S. Pat. No. 8,723,450 is not readily applicable or generic across different light fixtures. Finally, although the user is able to adjust the spectral content of the light output in the method disclosed in U.S. Pat. No. 8,723,450, the user is not provided control over or insight into how, for example, an object will appear when illuminated by the light output with the modified spectral content. In other words, the user is able to adjust the spectral content of the light output in U.S. Pat. No. 8,723,450 but does not have control over the lighting effect or effects (i.e., as perceived by a human observer or camera observer) created by the changing spectral content.

Embodiments described herein address this and other technical problems by analyzing aspects of perceived light to adjust the perceived appearance of the light output according to user specifications. The aspects of the perceived light controlled by embodiments described herein may include, for example, how the user perceives an object within the light output. In this way, the user alters the look and/or feel of the object according to how the user wants the object to appear. As a result, the user can alter how the object appears without altering the chromaticity of the light output. For example, the user may desire the object (e.g., human skin) to appear sickly under a metameric (constant-chromaticity) illuminant, or to appear brighter under a constant-power illuminant, or both.

Methods described herein provide for control of a light fixture, the method including energizing the light fixture to produce a first light output with a first chromaticity and a first spectral power distribution, receiving a user input representative of a desired adjustment of a lighting effect, generating a target spectrum based on the user input, and energizing the light fixture to produce a second light output with the first chromaticity and a second spectral power distribution. The second power distribution approximates the target spectrum.

Lighting control systems described herein include one or more light fixtures, one or more driver circuits, a user interface, and a controller. The one or more driver circuits are configured to provide drive signals to the one or more light fixtures. The user interface is configured to receive an input related to a light output of the one or more light fixtures. The input is representative of an adjustment of a lighting effect. The controller is connected to the one or more driving circuits and the user interface. The controller includes a processor and a memory. The controller is configured to energize the one or more light fixtures to produce a first light output with a first chromaticity and a first spectral power distribution, receive the input representative of the adjustment of the lighting effect, generate a target spectrum based on the input, and energize the one or more light fixtures to produce a second light output with the first chromaticity and a second spectral power distribution, the second power distribution approximates the target spectrum.

Controllers for controlling a light output of a light fixture described herein include a non-transitory computer readable medium and a processor. The controller includes computer executable instructions stored in the computer readable medium for controlling operation of the controller to energize the light fixture to produce a first light output with a first chromaticity and a first spectral power distribution, receive an input representative of an adjustment of a lighting effect, generate a target spectrum based on the user input, and energize the light fixture to produce a second light output with the first chromaticity and a second spectral power distribution, the second power distribution approximates the target spectrum.

It should be understood that the terms spectral match, spectrally matching, and the like (including similar terms with fixed or constant) refer to the application of an optimization procedure for spectrally matching the output composite light spectrum of the composite light source to a given target spectrum. It should be understood that the spectral match provided by the composite light source will not necessarily be identical to the target spectrum. But, it will be optimally close or as close as possible according to given system constraints. Similarly, the terms chromaticity match, chromaticity matching, constant chromaticity, fixed chromaticity, and the like refer to the application of an optimization procedure for matching CIE chromaticity coordinates of the output composite light source spectrum to CIE chromaticity coordinates of a given target spectrum. It should be understood that the chromaticity match provided by the composite light source will not necessarily be identical to the target spectrum. But, it will be optimally close or as close as possible according to given system constraints.

Before any embodiments are explained in detail, it is to be understood that the embodiments are not limited in their application to the details of the configuration and arrangement of components set forth in the following description or illustrated in the accompanying drawings. The embodiments are capable of being practiced or of being carried out in various ways. Also, it is to be understood that the phraseology and terminology used herein are for the purpose of description and should not be regarded as limiting. The use of "including," "comprising," or "having" and variations thereof are meant to encompass the items listed thereafter and equivalents thereof as well as additional items. Unless specified or limited otherwise, the terms "mounted," "connected," "supported," and "coupled" and variations thereof are used broadly and encompass both direct and indirect mountings, connections, supports, and couplings.

In addition, it should be understood that embodiments may include hardware, software, and electronic components or modules that, for purposes of discussion, may be illustrated and described as if the majority of the components were implemented solely in hardware. However, one of ordinary skill in the art, and based on a reading of this detailed description, would recognize that, in at least one embodiment, the electronic-based aspects may be implemented in software (e.g., stored on non-transitory computer-readable medium) executable by one or more processing units, such as a microprocessor and/or application specific integrated circuits ("ASICs"). As such, it should be noted that a plurality of hardware and software based devices, as well as a plurality of different structural components, may be utilized to implement the embodiments. For example, "servers" and "computing devices" described in the specification can include one or more processing units, one or more computer-readable medium modules, one or more input/output interfaces, and various connections (e.g., a system bus) connecting the components.

Other aspects of the embodiments will become apparent by consideration of the detailed description and accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a block diagram of a lighting control system.

FIG. **2** is a block diagram of a lighting control system according to another embodiment.

FIG. **3** illustrates a control interface for a lighting system.

FIG. **4** is a graph of the spectral reflectance function for an object.

FIG. **5** is a graph illustrating the spectral power distribution of light reflected off the object of FIG. **4** under a default condition, a positive hue shift condition, and a negative hue shift condition.

FIG. **6** is a CIE 1931 chromaticity diagram illustrating the chromaticity of the object of FIG. **4** under the default condition, the positive hue shift condition, and the negative hue shift condition of FIG. **5**.

FIG. **7**A is a TM-30 color vector graphic for the default condition of FIG. **5**.

FIG. **7**B is a TM-30 color vector graphic for the positive hue shift condition of FIG. **5**.

FIG. **7**C is a TM-30 color vector graphic for the negative hue shift condition of FIG. **5**.

FIG. **8**A is a graph illustrating a target output spectral power distribution and an achieved output spectral power distribution for the default condition of FIG. **5**.

FIG. **8**B is a graph illustrating a target output spectral power distribution and an achieved output spectral power distribution for the positive hue shift condition of FIG. **5**.

FIG. **8**C is a graph illustrating a target output spectral power distribution and an achieved output spectral power distribution for the negative hue shift condition of FIG. **5**.

FIG. **9** is a graph of the spectral reflectance function of an object.

FIG. **10**A is a TM-30 color vector graphic for a default condition for the object of FIG. **9**.

FIG. **10**B is a TM-30 color vector graphic for a positive chroma shift condition for the object of FIG. **9**.

FIG. **10**C is a TM-30 color vector graphic for a negative chroma shift condition for the object of FIG. **9**.

FIG. **11**A is a graph illustrating a target output spectral power distribution for the default condition of FIG. **10**A.

FIG. **11**B is a graph illustrating a target output spectral power distribution for the positive chroma shift condition of FIG. **10**B.

FIG. **11**C is a graph illustrating a target output spectral power distribution for the negative chroma shift condition of FIG. **10**C.

FIG. **12**A is a TM-30 color vector graphic for a default condition for a 5600K illuminant.

FIG. **12**B is a TM-30 color vector graphic for an oversaturated condition for the 5600K illuminant.

FIG. **12**C is a TM-30 color vector graphic for an undersaturated condition for the 5600K illuminant.

FIG. **13**A is a graph illustrating a target output spectral power distribution for the default condition of FIG. **12**A.

FIG. **13**B is a graph illustrating a target output spectral power distribution for the oversaturation condition of FIG. **12**B.

FIG. **13**C is a graph illustrating a target output spectral power distribution for the undersaturation condition of FIG. **12**C.

FIG. **14** is a graph of the spectral reflectance function of an object.

FIG. **15**A is a target output spectral power distribution for a non-white chromaticity at a default illuminance of the object of FIG. **14**.

FIG. **15**B is a target output spectral power distribution for the non-white chromaticity at an increased illuminance of the object of FIG. **14**.

FIG. **15**C is a target output spectral power distribution for the non-white chromaticity at a decreased illuminance of the object of FIG. **14**.

FIG. **16** is a graph illustrating the relative brightness of the object of FIG. **14**

FIG. **17** is a method for controlling a light output for a lighting system.

DETAILED DESCRIPTION

FIGS. **1** and **2** illustrate a control system **100** that can be used in, for example, a theatre, a hall, an auditorium, a hotel, a cruise ship, or the like. In some embodiments, the control system **100** is disposed within a light fixture. In other embodiments, only a portion of the control system **100** is disposed in the light fixture. The control system **100** is configured to generate a light output and project that light output onto an object **103** according to specifications of a user for how the object **103** is to appear in the light output. The object **103** may be a human (e.g., skin), an inanimate object (e.g., fruit or fabric), a wall, or the like. Additionally, the light output may be projected onto a plurality of objects **103** (e.g., a class of objects). For descriptive purposes, light is generally described as being projected onto the object **103**. However, in any instance where the object **103** is referenced, light can additionally be projected onto a plurality of objects **103** of the same or different classes of objects. The user specifications may alter the look and/or feel of the object **103** according to how the user wants the object to appear, which allows the user to alter how the object appears without altering the chromaticity of the light output.

The control system **100** includes a controller **105**, a plurality of light modules or light arrays **110**A-**110**C (e.g., light fixtures, color channels, etc.), a plurality of driver circuits **115**A-**115**C, a power control circuit **120**, an input mechanism **125**, and one or more indicators **130**. The controller **105** includes a plurality of electrical and electronic components that provide power, operational control, and protection to the components and modules within the controller **105** and/or the system **100**. For example, the controller **105** includes, among other things, a processing unit **135** (e.g., a microprocessor, a microcontroller, an electronic controller, an electronic processor, or another suitable programmable device), a memory **140**, input units **145**, and output units **150**. The processing unit **135** includes, among other things, a control unit **155**, an arithmetic logic unit ("ALU") **160**, and a plurality of registers **165** (shown as a group of registers in FIG. **1**), and is implemented using a known computer architecture (e.g., a modified Harvard architecture, a von Neumann architecture, etc.). The processing unit **135**, the memory **140**, the input units **145**, and the output units **150**, as well as the various modules connected to the controller **105** are connected by one or more control and/or data buses (e.g., common bus **170**). The use of one or more control and/or data buses for the interconnection between and communication among the various modules and components would be known to a person skilled in the art in view of the embodiments described herein. The control and/or data buses are shown generally for illustrative purposes.

In some embodiments, the control system **100** also includes a camera **175** configured to detect the light from the modules **110**A-**110**C reflected off of the object **103** (as shown in FIG. **1**). In some embodiments, the camera **175** is a spectrometer, or another device specifically designed to detect a light spectrum. In other embodiments, the control system **100** does not include the camera **175** (as shown in FIG. **2**). In these embodiments, the control system **100** operates in an open loop manner (i.e., without a closed-loop camera feedback system).

The memory **140** is a non-transitory computer readable medium and includes, for example, a program storage area and a data storage area. The program storage area and the data storage area can include combinations of different types of memory, such as a ROM, a RAM (e.g., DRAM, SDRAM, etc.), EEPROM, flash memory, a hard disk, an SD card, or other suitable magnetic, optical, physical, or electronic memory devices. The processing unit **135** is connected to the memory **140** and executes software instructions that are capable of being stored in a RAM of the memory **140** (e.g., during execution), a ROM of the memory **140** (e.g., on a generally permanent basis), or another non-transitory computer readable medium such as another memory or a disc. Software included in the implementation of the control system **100** can be stored in the memory **140** of the controller **105**. The software includes, for example, firmware, one or more applications, program data, filters, rules, one or more program modules, and other executable instructions. The controller **105** is configured to retrieve from the memory **140** and execute, among other things, instructions related to the control processes and methods described herein. In other embodiments, the controller **105** includes additional, fewer, or different components.

The user interface **125** is included to control the control system **100**. The user interface **125** is operably coupled to the controller **105** to control, for example, the output of the light modules **110**A-**110**C, and generate and provide control signals for the driver circuits **115**A-**115**C. The user interface **125** can include any combination of digital and analog input devices to achieve a desired level of control for the control system **100**. For example, the user interface **125** can include a computer having a display and input devices, a touch-screen display, a plurality of knobs, dials, switches, buttons, faders, or the like. In some embodiments, the user interface **125** is separated from the control system **100** (e.g., as a portable device communicatively connected to the controller **105**).

The driver circuits **115**A-**115**C include a first driver circuit **115**A, a second driver circuit **115**B, and a third driver circuit **115**C that are operable to provide control signals to the light modules **110**A-**110**C. For example, the first driver circuit **115**A is connected to a first light module **110**A for providing one or more drive signals to an array of (i.e., one or more) light sources of the first light module **110**A. The second driver circuit **115**B is connected to a second light module **110**B for providing one or more drive signals to an array of (i.e., one or more) light sources on the second light module **110**B. The third driver circuit **115**C is connected to a third light module **110**C for providing one or more drive signals to an array of (i.e., one or more) light sources on the third light module **110**C. In some embodiments, each of the light modules **110**A-**110**C corresponds to a color channel of a light. In other embodiments, each of the light modules **110**A-**110**C corresponds to a separate light fixture.

The power control circuit **120** supplies a nominal AC or DC voltage to the control system **100**. In some embodiments, the power control circuit **120** is powered by one or more batteries or battery packs. In other embodiments, the power control circuit **120** is powered by mains power having nominal line voltages between, for example, 100V and 240V AC and frequencies of approximately 50-60 Hz. The power control circuit **120** is also configured to supply lower voltages to operate circuits and components within the control system **100**.

As illustrated in FIGS. **1** and **2**, the controller **105** is connected to light modules **110**A-**110**C. In some embodiments, each light module **110**A-**110**C is a chip-on-board ("COB") light source. A three light module embodiment is illustrated for exemplary purposes only. In other embodiments, four or more light modules are used to further enhance the system **100**'s ability to produce visible light. Conversely, in other implementations, fewer than three light modules are used (i.e., one or two light modules). In some embodiments, the light modules **110**A-**110**C are light emitting diode ("LED") light modules. In some embodiments, the light modules **110**A-**110**C produce white light. In other embodiments, the light modules **110**A-**110**C produce colored light (i.e., non-white light).

The control system **100** further includes a control interface **200** (see FIG. **3**) for controlling a visual appearance of the light output light from the light modules **110**A-**110**C that is, for example, reflected from the object **103**. In some embodiments, the control interface **200** is included in the user interface **125**. The control interface **200** is, for example, a graphical user interface ("GUI") that is displayed on a monitor or similar display. In some embodiments, the control interface **200** is a physical interface and includes one or more buttons, knobs, dials, faders, or the like.

The illustrated control interface **200** includes an optional enable parametric rendering adjustment section **205**, a first lighting effect level section **210**, and a second lighting effect level section **215**. The enable parametric rendering adjustment section **205** includes a YES checkbox **220** and a NO checkbox **225**. The checkboxes **220** and **225** are used to select or deselect parametric rendering adjustment (i.e., control based on visual appearance of the lighting effect).

The parametric rendering adjustment can use the first lighting effect level section **210** and/or the second lighting effect level section **215** to implement lighting effects that modify the appearance of light, for example, reflected off the object **103**. The first and second lighting effect level of the sections **210**, **215** may include control of quality, luminance, hue, power, color temperature, or the like. The first and second lighting effects are generic to any light fixture and allows the user to control effects to the best of the system's ability, regardless of what light fixture is used.

In some embodiments, the parametric rendering adjustment includes more than two lighting effect level sections. In the illustrated embodiment, each of the lighting effect level sections includes a maximum value and a minimum value. For the purposes of this embodiment, the maximum value is a value of positive 100 (e.g., oversaturation). The minimum value is a value of negative 100 (e.g., undersaturation). For example, the maximum undersaturation value is the inverse of the maximum oversaturation value. The first and second lighting effect level sections **210**, **215** each include a slider **230** and a drop-down menu **235**. The slider **230** ranges from negative 100 to positive 100 (e.g., from undersaturation to oversaturation). The drop-down menu **235** ranges from −100% to 100%. In other embodiments, the first and second lighting effect level sections **210** include different selection mechanisms. In conventional lighting control systems, the first and second lighting effects are not directly controllable along a continuum (i.e., negative 100 to positive 100). In this way, the control interface **200** permits the user to precisely control aspects of the output light that would not otherwise be directly adjustable and controllable by conventional controls, all while maintaining the same output chromaticity. Non-limiting examples of lighting effects to be controlled by the interface **200** are described in further detail herein.

With reference to FIGS. **4**-**8**C, in one embodiment, the lighting effect controlled by the interface **200** is the hue shift of an objected illuminated by the light output of the light arrays **110**A-**110**C. With this control, the illuminated object **103** may appear to an observer (i.e., a human or camera) to be different colors and can be adjusted by a user while holding the output light chromaticity constant.

With reference to FIG. **4**, a spectral reflectance function **300** of a first example object (e.g., a grapefruit) is illustrated. The spectral reflectance function **300** illustrates how incoming light will be reflected off the object—with longer wavelengths (e.g., greater than 600 nm) reflected more than shorter wavelengths. With the control interface **200**, the hue of the first example object may be controlled between a default condition, a positive hue shift condition (e.g., +100 adjustment of the first lighting effect level section **210**), and a negative hue shift condition (e.g., −100 adjustment of the first lighting effect level section **210**). In other words, the control interface **200** is utilized by a user to control the color appearance of the first example object without changing the chromaticity of the output light. For each of these conditions, the resulting spectral power distribution of light reflected off the first example object (i.e., the grapefruit's rendered spectra) is illustrated in FIG. **5**. Specifically, the rendered spectrum **305** is for the default condition, the rendered spectrum **310** is for the positive hue shift condition, and the rendered spectrum **315** for the negative hue shift condition.

With reference to FIG. **6**, each of these rendered spectrums **305**, **310**, **315** correspond to an object chromaticity **320**, **325**, **330** as illustrated in a CIE 1931 chromaticity diagram. More specifically, the first example object appears to an observer at a default chromaticity **320** with an output light chromaticity **318**. In the illustrated embodiment, the output light chromaticity **318** is on the Planckian locus **319** and is held constant. The first example object appears to an observer at a positive hue shift chromaticity **325** in the positive hue shift condition and at a negative hue shift chromaticity **330** in the negative hue shift condition. As such, the control interface **200** permits a user to adjust the chromaticity of the light reflected off of the first example object while maintaining the output light chromaticity constant.

With reference to FIGS. **7**A-**7**C, color vector graphics are illustrated according to the TM-30 standard. In general, a color vector graphic shows how the color evaluation samples, representative of a wide range of objects, are likely to undergo either a saturation (chroma) shift, a hue shift, or both. The color vector graphic is divided into 16 equal sections with for, example, section **1** representative of red and section **9** representative of cyan. The reference illuminant is normalized to a reference circle **350** and the gamut of the light source is plotted relative to the circle as a distorted circle (e.g., **360** of FIG. **7**B). Arrows that point radially into the reference circle **350** indicate areas of decreased saturation while areas that point radially out of the reference circle **350** indicate areas of increased saturation. Arrows that do not point directly to the center of the circle **350** or directly away from the center **350** of the circle are representing hue shift. In short, the color vector graphics can be used to illustrate how objects will appear in an output light relative to a reference light source (e.g., daylight).

With continued reference to FIGS. **7**A-**7**C, the color vector graphics are illustrated for the default condition (FIG. **7**A), the positive hue shift condition (FIG. **7**B), and the negative hue shift condition (FIG. **7**C). In FIG. **7**A, the light source output gamut **355** closely tracks the reference circle **350** in the default condition. Attributes of the output light (R_f, R_g, CCT, D_{uv}) in the default condition are also listed in FIG. **7**A. In FIG. **7**B, the light source output gamut **360** is adjusted in the positive hue shift condition, and in FIG. **7**C, the light source output gamut **365** is adjusted in the negative hue shift condition. The CCT value of 3200 K and D_{uv} of 0.0000 is held constant for FIGS. **7**A-**7**C.

To achieve the default, positive hue shift, and negative hue shift conditions desired by the user, the controller **105** determines the corresponding target output light spectrums **370**, **380**, **390** illustrated in FIGS. **8**A-**8**C. The target output light spectrums **370**, **380**, **390** correspond to the default, positive hue shift, and negative hue shift conditions, respectively, and may be determined by selecting one of the many possible metamers for the target chromaticity (e.g., **318**). In other words, there are numerous metamers for the target chromaticity (e.g., **318**) and the controller **105** selects the metamer that results in the hue shift condition desired by the user. The selection of the metamer for a desired hue shift may be preprogrammed into the memory **140** as a look-up table, for example. In other embodiments, the metamer could also be calculated by methods including, but not limited to, live calculation within the luminaire, live calculation within the controller, stored spectrum, spectrum measured live using a suitable sensor, chromaticity point measured live using a suitable sensor, further input from the user, learned behavior based on a user's previous selections, learned behavior based on a user's stored preferences, or combinations thereof.

With the target output light spectrums **370**, **380**, **390** determined, conventional spectral matching techniques (such as those disclosed in U.S. Pat. No. 6,683,423; incorporated herein) are utilized to determine how to drive the actual light emitters contained within a given fixture. In other words, the control system **100** determines an idealized target output spectrum for controlling the hue shift of the first example object. As one example, the actual output spectral power distribution achieved for an example light fixture containing eight primary emitters is illustrated as output spectrum distributions **375**, **385**, **395** on FIGS. **8**A-**8**C. In other words, the output spectrum distributions **375**, **385**, **395** illustrate a given light fixture's best ability to match the target output light spectrums **370**, **380**, **390**.

In summary, FIGS. **4**-**8**C illustrate the implementation of control for hue shift of a first example object illuminated by a light fixture (i.e., an example light effect level). With the control interface **200**, a user adjusts the light that is reflected off of the first example object (i.e., change in reflected light chromaticities **320**, **325**, **330**), while holding the output light chromaticity constant (e.g., chromaticity **318**). The hue shift of the first example object is not directly adjustable with conventional controls.

With reference to FIGS. **9**-**11**C, in another embodiment, the lighting effect controlled by the interface **200** is the chroma shift of an object illuminated by the light output of the light arrays **110**A-**110**C. With this control, the illuminated object **103** may appear to an observer (i.e., a human or camera) to be different saturations and can be adjusted by a user while holding the output light chromaticity constant.

With reference to FIG. **9**, a spectral reflectance function **400** of a second example object (e.g., one example of human skin) is illustrated. The spectral reflectance function **400** illustrates how incoming light will be reflected off the second example object. With the control interface **200**, the chroma (i.e., saturation) of the second example object may be controlled between a default condition, a positive chroma shift condition (e.g., +100 adjustment of the first lighting effect level section **210**), and a negative chroma shift condition (e.g., −100 adjustment of the first lighting effect level section **210**). In other words, the control interface **200** is utilized by a user to control the saturation appearance of the second example object without changing the chromaticity of the output light. As such, the R_g value of the output light is adjusted to be greater than or less than 100.

With reference to FIGS. **10**A-**10**C, the color vector graphics are illustrated for the default condition (FIG. **10**A), the positive chroma shift condition (FIG. **10**B), and the negative chroma shift condition (FIG. **10**C). In FIG. **10**A, the light source output gamut **405** closely tracks the reference circle **402** in the default condition and the R_g value is 100. Attributes of the output light (R_f, CCT, D_{uv}) in the default condition are also listed in FIG. **10**A. In FIG. **10**B, the light source output gamut **410** is adjusted in the positive chroma shift condition with a R_g value of 106, and in FIG. **10**C, the light source output gamut **415** is adjusted in the negative chroma shift condition with a R_g value of 90. The CCT value of 4000 K and D_{uv} of 0.0000 is held constant for FIGS. **10**A-**10**C.

With reference to FIGS. **11**A-**11**C, for each of the desired chroma-shifts in the second example object there is a corresponding output target spectrum power distribution **420**, **425**, **430**. The target output light spectrums **420**, **425**, **430** correspond to the default, positive chroma shift, and negative chroma shift conditions, respectively, and may be determined by selecting one of the many possible metamers for the target chromaticity (e.g., CCT=4000 K and D_{uv}=0.0000). In other words, there are numerous metamers for the target chromaticity and the controller **105** selects the metamer that results in the chroma shift condition for the second example object desired by the user. The selection of the metamer for a desired chroma shift may be preprogrammed into the memory **140** as a look-up table, for example. In other embodiments, the metamer could also be calculated by methods including, but not limited to, live calculation within the luminaire, live calculation within the controller, stored spectrum, spectrum measured live using a suitable sensor, chromaticity point measured live using a suitable sensor, further input from the user, learned behavior based on a user's previous selections, learned behavior based on a user's stored preferences, or combinations thereof. The target output light spectrums **420**, **425**, **430** are generalized targets (similar to the target spectrum **370**, **380**, **390**) that are applicable to any type of light fixture being used. Conventional target spectral matching techniques may be utilized to drive emitters in a given light fixture in order to approximate the target.

In summary, FIGS. **9**-**11**C illustrate the implementation of control for chroma shift of a second example object illuminated by a light fixture (i.e., an example light effect level). With the control interface **200**, a user adjusts the saturation of the light reflected off of the second example object, while holding the output light chromaticity constant. The chroma shift of the second example object is not directly adjustable with conventional controls.

With reference to FIGS. **12**A-**13**C, in another embodiment, the lighting effect controlled by the interface **200** is the generalized saturation appearance of object(s) (i.e., R_g value) of an approximately 5600 K light output of the light arrays **110**A-**110**C. With the control interface **200**, the generalized saturation may be controlled between a default condition, a generalized oversaturated condition (e.g., +100 adjustment of the first lighting effect level section **210**), and a generalized undersaturation condition (e.g., −100 adjustment of the first lighting effect level section **210**). In other words, the control interface **200** is utilized by a user to control the generalized saturation appearance of object(s) without changing the chromaticity of the output light. As such, the R_g value of the output light is adjusted to be greater than or less than 100.

With reference to FIGS. **12**A-**12**C, the color vector graphics are illustrated for the default condition (FIG. **12**A), the generalized oversaturation condition (FIG. **12**B), and the generalized undersaturation condition (FIG. **12**C). In FIG. **12**A, the light source output gamut **505** closely tracks the reference circle **502** in the default condition and the R_g value is 100. Attributes of the output light (R_f, CCT, D_{uv}) in the default condition are also listed in FIG. **12**A. In FIG. **12**B, the light source output gamut **510** is adjusted in the generalized oversaturation condition with a R_g value of 110, and in FIG. **12**C, the light source output gamut **515** is adjusted in the generalized undersaturation condition with a R_g value of 91. The CCT value of 5599 K and D_{uv} of 0.0032 is held constant for FIGS. **12**A-**12**C.

With reference to FIGS. **13**A-**13**C, for each of the desired generalized saturation levels there is a corresponding output target spectrum power distribution **520**, **525**, **530**. The target output light spectrums **520**, **525**, **530** correspond to the default, oversaturated, and undersaturated conditions, respectively, and may be determined by selecting one of the many possible metamers for the target chromaticity (e.g., CCT=5599 K and D_{uv}=0.0032). In other words, there are numerous metamers for the target chromaticity and the controller **105** selects the metamer that results in the generalized saturation level desired by the user. The selection of the metamer for a desired saturation level may be preprogrammed into the memory **140** as a look-up table, for example. In other embodiments, the metamer could also be calculated by methods including, but not limited to, live calculation within the luminaire, live calculation within the controller, stored spectrum, spectrum measured live using a suitable sensor, chromaticity point measured live using a suitable sensor, further input from the user, learned behavior based on a user's previous selections, learned behavior based on a user's stored preferences, or combinations thereof. The target output light spectrums **520**, **525**, **530** are generalized targets (similar to the target spectrum **370**, **380**, **390**) that are applicable to any type of light fixture being used.

In summary, FIGS. **12**A-**13**C illustrate the implementation of control for generalized saturation appearance of object(s) in an approximately 5600K illuminant (i.e., an example light effect level), while holding the output light chromaticity constant. The generalized saturation of a 5600K illuminant is not directly adjustable with conventional controls.

With reference to FIGS. **14-16**, in another embodiment, the lighting effect controlled by the interface **200** is the relative luminance of an object illuminated by a non-white light output of the light arrays **110**A-**110**C. With this control, the illuminated object **103** may appear to an observer (i.e., a human or camera) to be brighter or darker and can be adjusted by a user while holding the output light chromaticity constant at a non-white color and equal luminous flux.

With reference to FIG. **14**, a spectral reflectance function **600** of a third example object (e.g., a purple scarf) is illustrated. The spectral reflectance function **600** illustrates how incoming light will be reflected off the third example object. With the control interface **200**, the luminance (i.e., brightness) of the third example object may be controlled between a default condition (point **605** in FIG. **16**), an increased relative luminance condition (point **610** in FIG. **16**) (e.g., +100 adjustment of the first lighting effect level section **210**), and a decreased relative luminance condition (point **615** in FIG. **16**) (e.g., −100 adjustment of the first lighting effect level section **210**). The minimum (e.g., −100 from the interface **200** of FIG. **3**) and maximum (e.g., +100 from the interface **200** of FIG. **3**) are defined as the extremes of the lighting effect adjustment. The changes that occur to the target output spectrum between the spectrums **625**, **630** for the minimum and maximum control levels, respectively, can then be mapped (e.g., linearly) to produce a target spectrum for control values between −100 and 100 for a controllable lighting effect. In other words, the control interface **200** is utilized by a user to control the luminance of the third example object without changing the chromaticity of the output light—which in this example is a blue output light. The brightness of the third example object is being adjusted relative to the rest of the scene illuminated, since the luminous flux of the output light is held constant.

With reference to FIGS. **15**A-**15**C, for each of the desired relative brightnesses of the third example object there is a corresponding output target spectrum power distribution **620**, **625**, **630**. The target output light spectrums **620**, **625**, **630** correspond to the default, increased relative brightness, and decreased relative brightness conditions, respectively, and may be determined by selecting one of the many possible metamers for the target chromaticity (e.g., blue, or "steel blue"). In other words, there are numerous metamers for the target chromaticity and the controller **105** selects the metamer that results in the relative brightness condition for the third example object desired by the user. The selection of the metamer for a desired relative luminance may be preprogrammed into the memory **140** as a look-up table, for example. The target output light spectrums **620**, **625**, **630** are generalized targets (similar to the target spectrums **370**, **380**, **390**) that are applicable to any type of light fixture being used.

Although the described embodiment uses a look-up table to calculate a metamer, in other embodiments, the metamer could also be calculated by methods including, but not limited to, live calculation within the luminaire, live calculation within the controller, stored spectrum, spectrum measured live using a suitable sensor, chromaticity point measured live using a suitable sensor, further input from the user, learned behavior based on a user's previous selections, learned behavior based on a user's stored preferences, or combinations thereof.

In summary, FIGS. **14-16** illustrate the implementation of control for relative brightness of a third example object illuminated by a light fixture (i.e., an example light effect level). With the control interface **200**, a user adjusts the luminance of the light reflected off of the third example object relative to its surroundings, while holding the output light chromaticity constant at a non-white color and equal luminous flux. The relative luminance of the third example object illuminated by non-white light is not directly adjustable with conventional controls.

FIG. **17** illustrates a method **700** for using the control system **100** to adjust a lighting effect of the output light from light arrays **110**A-**110**C. Various steps described herein with respect to the process **700** are capable of being executed simultaneously, in parallel, or in an order that differs from the illustrated serial manner of execution.

In some embodiments, the user enables the parametric rendering adjustment and alters the first lighting effect level **210** and/or the second lighting effect level **215** on the control interface **200** (see FIG. **3**) to control the visual appearance of light on the object **103** (STEP **705**). In other embodiments, enabling parametric rendering adjustment is not specifically required. Before any adjustments are made, the method **700** includes energizing the light fixture to produce a first light output with a first chromaticity and a first spectral power distribution (STEP **710**). In other words, the light fixture generates a default light output. The controller **105** receives signals related to a user input that is representative of a desired adjustment of a lighting effect (STEP **715**). The desired adjustment of a lighting effect may include adjustment of the Illumination Engineering Society ("IES") Technical Memorandum 30 ("TM-30") R_g value of the light output; adjustment of a hue shift in an object illuminated by the light output; or adjustment of a chroma shift in an object illuminated by the light output. In other embodiments, the desired adjustment of a lighting effect may include adjustment of one or more parameters or metrics of a light output including but not limited to; Television Lighting Consistency Index ("TLCI"); Color Rendering Index ("CRI") R_a; CRI R9; Spectral Similarity Index ("SSI"); TM-30 R_f; TM-30 R_g; TM-30 $R_{cs,h1}$; TM-30 $Rf_{f,h1}$; TM-30 Annex E's PVF (Preference, Vividness, Fidelity) values; Color Quality

Scale ("CQS"); Pigment/dye/colorant alignment; Skin tone quality; Vibrance/richness; Increase or decrease in fluorescence or excitation of optical brighteners; generalized Cool/Warm appearance shift; Light source selection (e.g., tungsten 3200K vs HID 3200K vs fluorescent 3200K). Such adjustments may be applied independently or simultaneously in any combination of multiple parameters. In other embodiments, the desired adjustment of a lighting effect includes adjustment of a relative luminance of an object illuminated by the light output. In a further embodiment the desired adjustment of a lighting effect is to adjust skin tone rendition by suppressing or enhancing the cyan wavelengths. This adjustment, while maintaining a chromaticity match or constant chromaticity, provides the user the ability to tune the appearance of skin tones both to the eye and to a camera.

The method **700** further includes generating a target output light spectrum based on the user input received (STEP **720**). In some embodiments, the target spectrum is retrieved from a look-up table stored in the memory **140**. In other embodiments, the metamer could also be calculated by methods including, but not limited to, live calculation within the luminaire, live calculation within the controller, stored spectrum, spectrum measured live using a suitable sensor, chromaticity point measured live using a suitable sensor, further input from the user, learned behavior based on a user's previous selections, learned behavior based on a user's stored preferences, or combinations thereof. The method **700** includes energizing the light fixture to produce a second light output with the first chromaticity and a second spectral power distribution (STEP **725**). The second spectral power distribution approximates or matches the target spectrum and will depend on the type of light fixture utilized to create the target spectrum.

The inputted first and/or second lighting effect levels **210**, **215** are used to modify a spectrum of light produced by the light modules **110**A-**110**C. If the appearance of the object **103** is not satisfactory, the user can modify the first lighting effect level **210** and/or the second lighting effect level **215** on the control interface **200**. In this way, the control is open-loop and based on user observations and adjustments. As such, the controller **105** is configured to dynamically alter the light output to achieve a desired visual appearance of the object **103**, for example. In some embodiments, the light projected onto the object **103** can be white light or colored light (i.e., light other than white light), as shown in FIGS. **14-16**.

In some embodiments, the camera **175** can be used to detect a reflectance of the light off of the object **103** (STEP **730**). Based on the reflectance of light off of the object **103**, as detected by the camera **175**, further adjustments to the target output light spectrum may be made. In this sense, the control may provide a closed-loop system that detects and measures the lighting effect being adjusted. In some embodiments, STEP **730** is not included.

Thus, embodiments described herein provide, among other things, systems, methods, and devices for controlling a light output based on a visual appearance of one or more objects. Various features and advantages are set forth in the following claims.

What is claimed is:

1. A lighting control system comprising:

one or more light sources;

one or more driver circuits configured to provide drive signals to the one or more light sources;

an interface configured to receive an input related to a light output of the one or more light sources, the input being related to an adjustment of a lighting effect; and

a controller connected to the one or more driving circuits and the interface, the controller including a processor and a memory, the controller configured to:

control the one or more light sources to produce a first light output with a first chromaticity and a first spectral power distribution,

receive the input related to the adjustment of the lighting effect,

generate a target spectrum based on the input, and

control the one or more light sources to produce a second light output with the first chromaticity and a second spectral power distribution, the second power distribution approximating the target spectrum.

2. The lighting control system of claim **1**, wherein the first chromaticity is a non-white color.

3. The lighting control system of claim **1**, wherein the interface includes a selection mechanism for selecting a value for the lighting effect.

4. The lighting control system of claim **3**, wherein the value for the lighting effect can have a positive value or a negative value.

5. The lighting control system of claim **4**, wherein the positive value corresponds to oversaturation and the negative value corresponds to undersaturation.

6. The lighting control system of claim **1**, wherein the one or more light sources include one or more chip-on-board ("COB") light sources.

7. The lighting control system of claim **1**, further comprising:

a camera configured to detect light from the one or more light sources that is reflected off of an object.

8. The lighting control system of claim **7**, wherein the camera is a spectrometer.

9. The lighting control system of claim **7**, wherein the target spectrum is modified based on the light that is reflected off of the object.

10. The lighting control system of claim **1**, wherein the lighting effect is one selected from the group consisting of: the TM-30 R_g value of the light output, a hue shift of the light reflected by an object illuminated by the light output, a chroma shift of the light reflected by an object illuminated by the light output, a Television Lighting Consistency Index ("TLCI") value of the light output, a Color Rendering Index ("CRI") Ra value of the light output, a Spectral Similarity Index ("SSI") value of the light output, the relative luminance of an object illuminated by the light output, the TM-30 R_f value of the light output, the TM-30 $R_{cs,h1}$ value of the light output, and the TM-30 $R_{f,h1}$ value of the light output.

11. A method for controlling a light source, the method comprising:

controlling the light source to produce a first light output with a first chromaticity and a first spectral power distribution;

receiving an input related to a desired adjustment of a lighting effect;

generating a target spectrum based on the input; and

controlling the light source to produce a second light output with the first chromaticity and a second spectral power distribution, the second power distribution approximating the target spectrum.

12. The method of claim **11**, wherein the first light output has a first lumen output and the second light output has a second lumen output equal to the first lumen output.

13. The method of claim **11**, further comprising:

receiving, via a selection mechanism of the interface, a value for the lighting effect.

14. The method of claim **13**, wherein the value for the lighting effect can have a positive value or a negative value.

15. The method of claim **14**, wherein the positive value corresponds to oversaturation and the negative value corresponds to undersaturation.

16. The method of claim **11**, further comprising:

detect light from the one or more light sources that is reflected off of an object; and

modifying the target spectrum based on the light that is reflected off of the object.

17. The method of claim **11**, wherein generating the target spectrum based on the input includes retrieving the target spectrum from a table stored in a memory.

18. The method of claim **11**, wherein the lighting effect is one selected from the group consisting of: the TM-30 R_g value of the light output, a hue shift of the light reflected by an object illuminated by the light output, a chroma shift of the light reflected by an object illuminated by the light output, a Television Lighting Consistency Index ("TLCI") value of the light output, a Color Rendering Index ("CRT") Ra value of the light output, a Spectral Similarity Index ("SST") value of the light output, the relative luminance of an object illuminated by the light output, the TM-30 R_f value of the light output, the TM-30 $R_{cs,h1}$ value of the light output, and the TM-30 $R_{f,h1}$ value of the light output.

19. A controller for controlling a light output of a light source, the controller including a non-transitory computer readable medium and a processor, the controller including computer executable instructions stored in the computer readable medium for controlling operation of the controller to:

control the light source to produce a first light output with a first chromaticity and a first spectral power distribution;

receive an input related to an adjustment of a lighting effect;

generate a target spectrum based on the input; and

control the light source to produce a second light output with the first chromaticity and a second spectral power distribution, the second power distribution approximating the target spectrum.

20. The controller of claim **19**, the controller further including computer executable instructions stored in the computer readable medium for controlling operation of the controller to:

receive, via a selection mechanism of an interface, a value for the lighting effect.

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