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Bewick et al.

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(54) **SYSTEM AND METHOD FOR CONTROLLING A PLURALITY OF LIGHT FIXTURE OUTPUTS**

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(Continued)

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(58) **Field of Classification Search**

USPC .... 315/185 R, 192, 291, 294, 297, 299, 315/307, 308, 312

See application file for complete search history.

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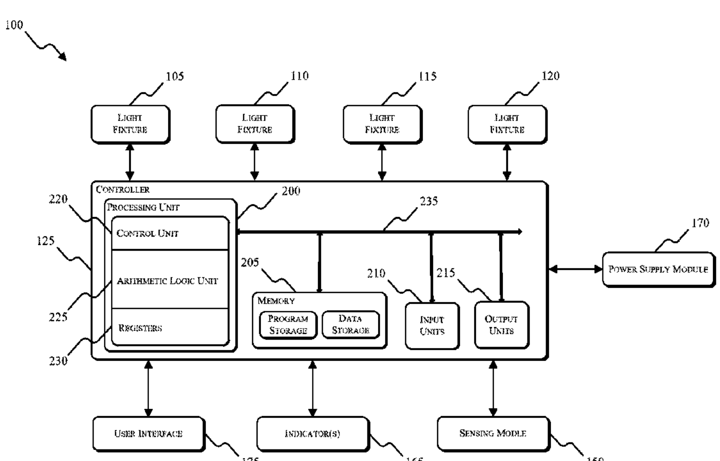
(57) **ABSTRACT**

A method of controlling a plurality of light fixtures. The method includes detecting the light outputs of a plurality of light fixtures and detecting a reflection of light from a surface. The light outputs and the reflection of light are analyzed. Differences among the light outputs of the plurality of light fixtures are determined, and a difference between the reflection of light and a desired reflection of light is determined. New or updated values for output color, output brightness, and/or output spectra are determined for the plurality of light fixtures such that the light outputs of the light fixtures are consistent and correspond to a desired light output, and such that the reflection of light corresponds to the desired reflection of light. Each of the plurality of light fixtures is then driven using respective light source output values to produce the desired light outputs.

17 Claims, 7 Drawing Sheets



(51) **Int. Cl.**
H05B 37/02 (2006.01)
H05B 39/04 (2006.01)

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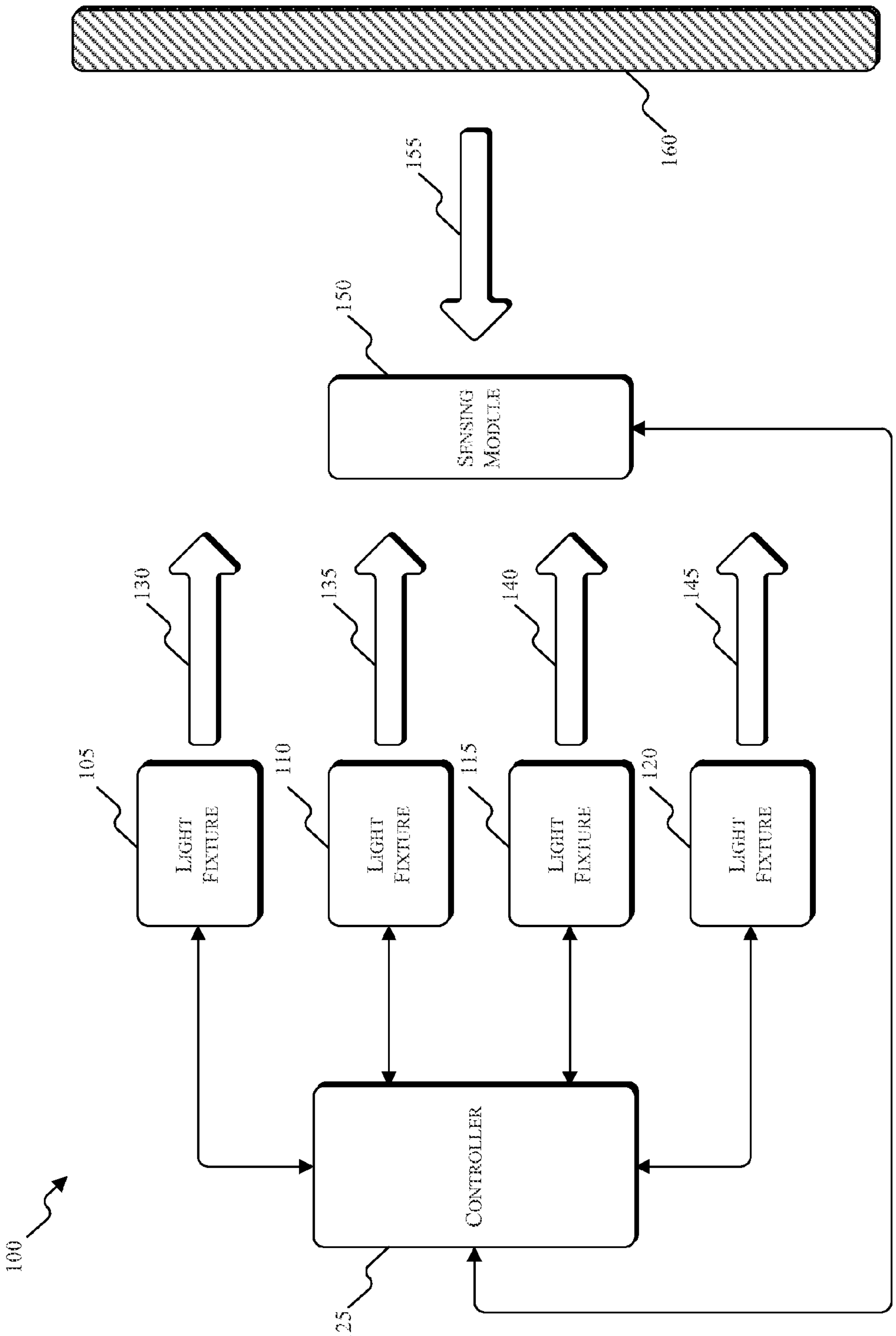

100
105
110
115
120
Light Fixture
Light Fixture
Light Fixture
Light Fixture
125
Controller
130
135
140
145
150
Sensing Module
155
160

FIG. 1

FIG. 2

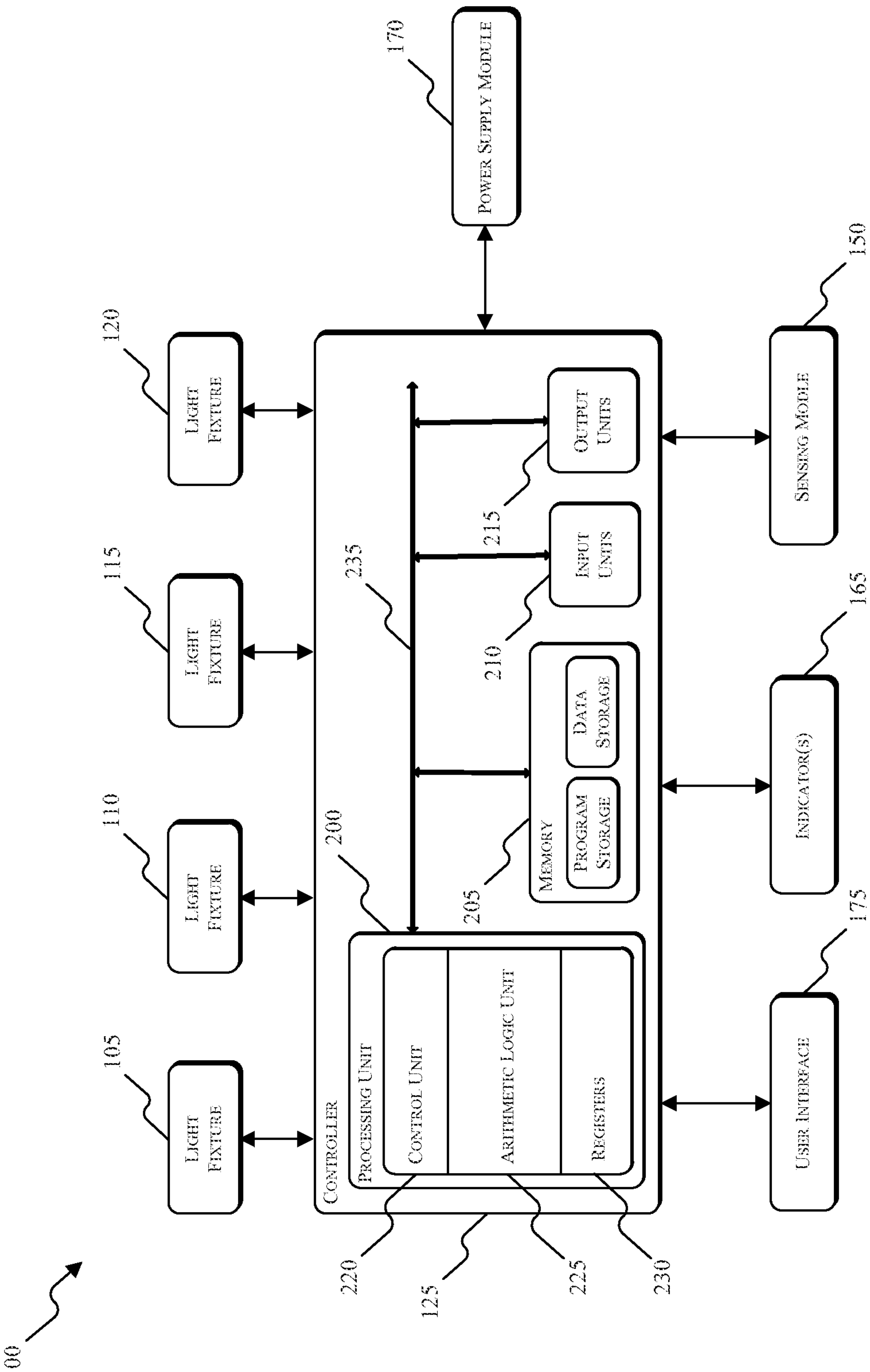

100
105
Light Fixture
110
Light Fixture
115
Light Fixture
120
Light Fixture
170
Power Supply Module
125
Controller
200
Processing Unit
Control Unit
Arithmetic Logic Unit
Registers
220
225
230
235
205
Memory
Program Storage
Data Storage
210
Input Units
215
Output Units
150
Sensing Module
165
Indicator(s)
175
User Interface

FIG. 3

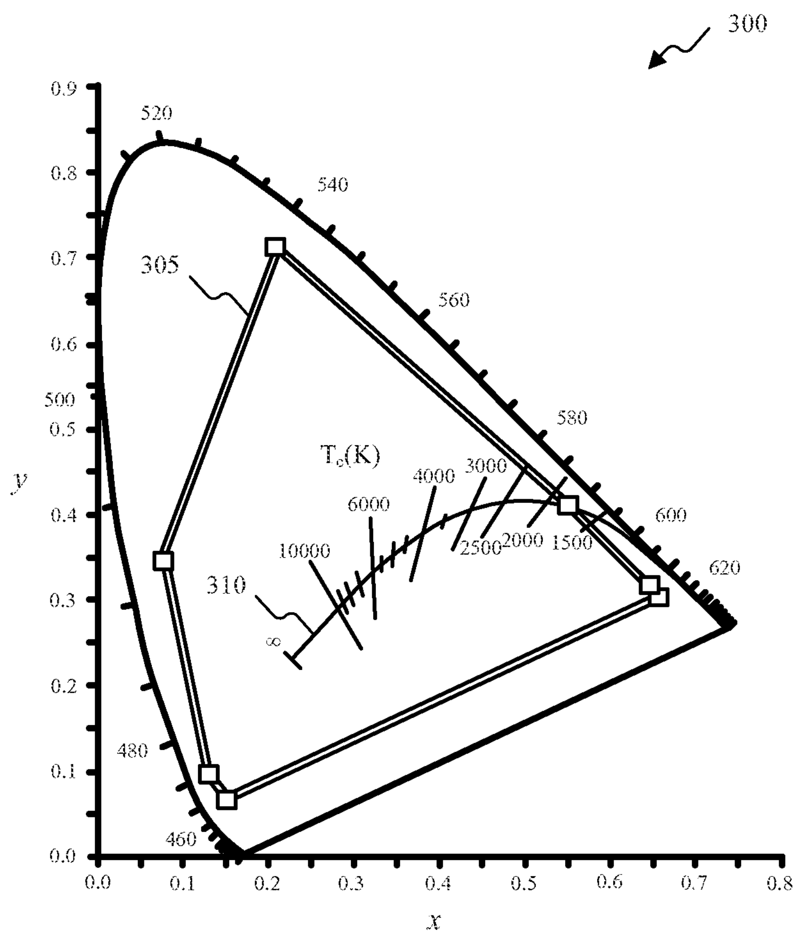

300
305
310
520
540
560
580
600
620
500
480
460
T_c(K)
10000
6000
4000
3000
2500
2000
1500
∞
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
x
y

FIG. 4

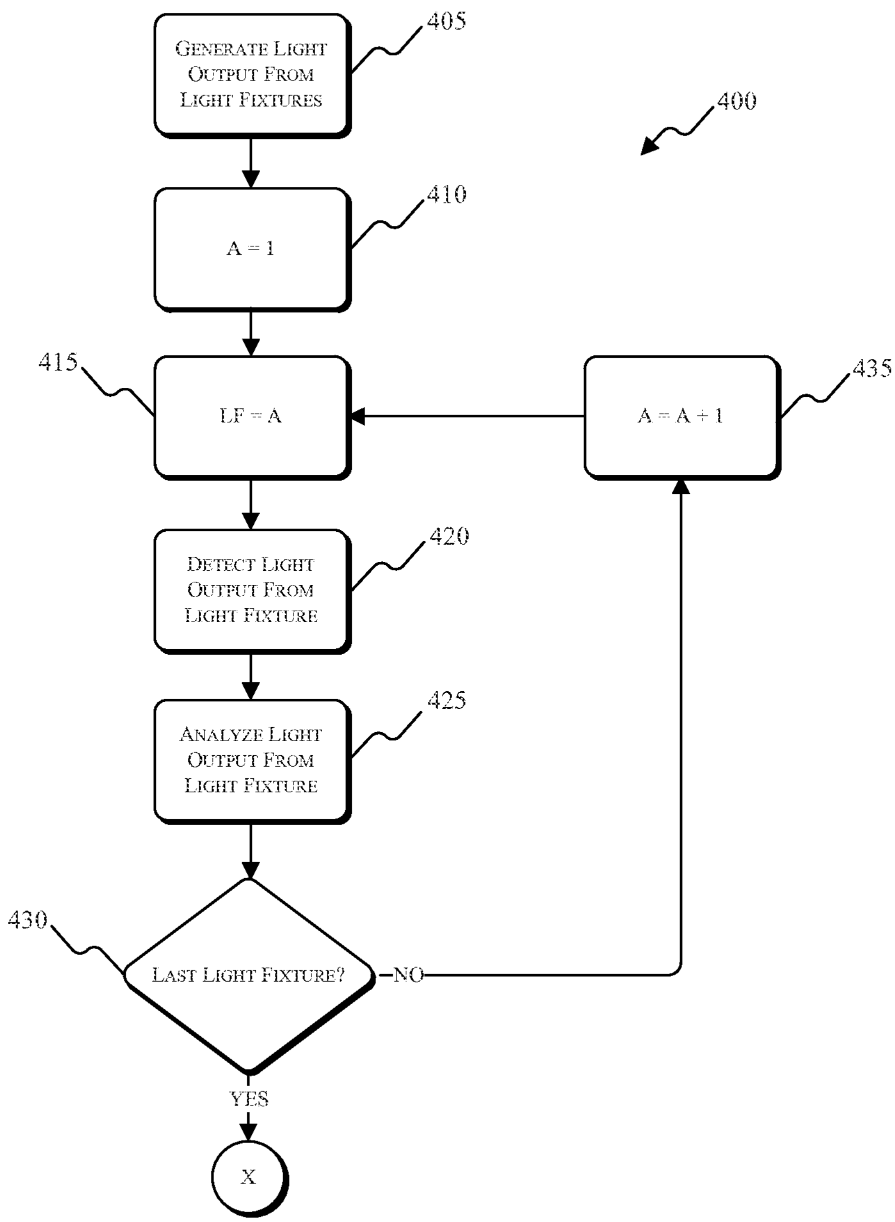

400
405
Generate Light Output From Light Fixtures
410
A = 1
415
LF = A
435
A = A + 1
420
Detect Light Output From Light Fixture
425
Analyze Light Output From Light Fixture
430
Last Light Fixture?
NO
YES
X

FIG. 5

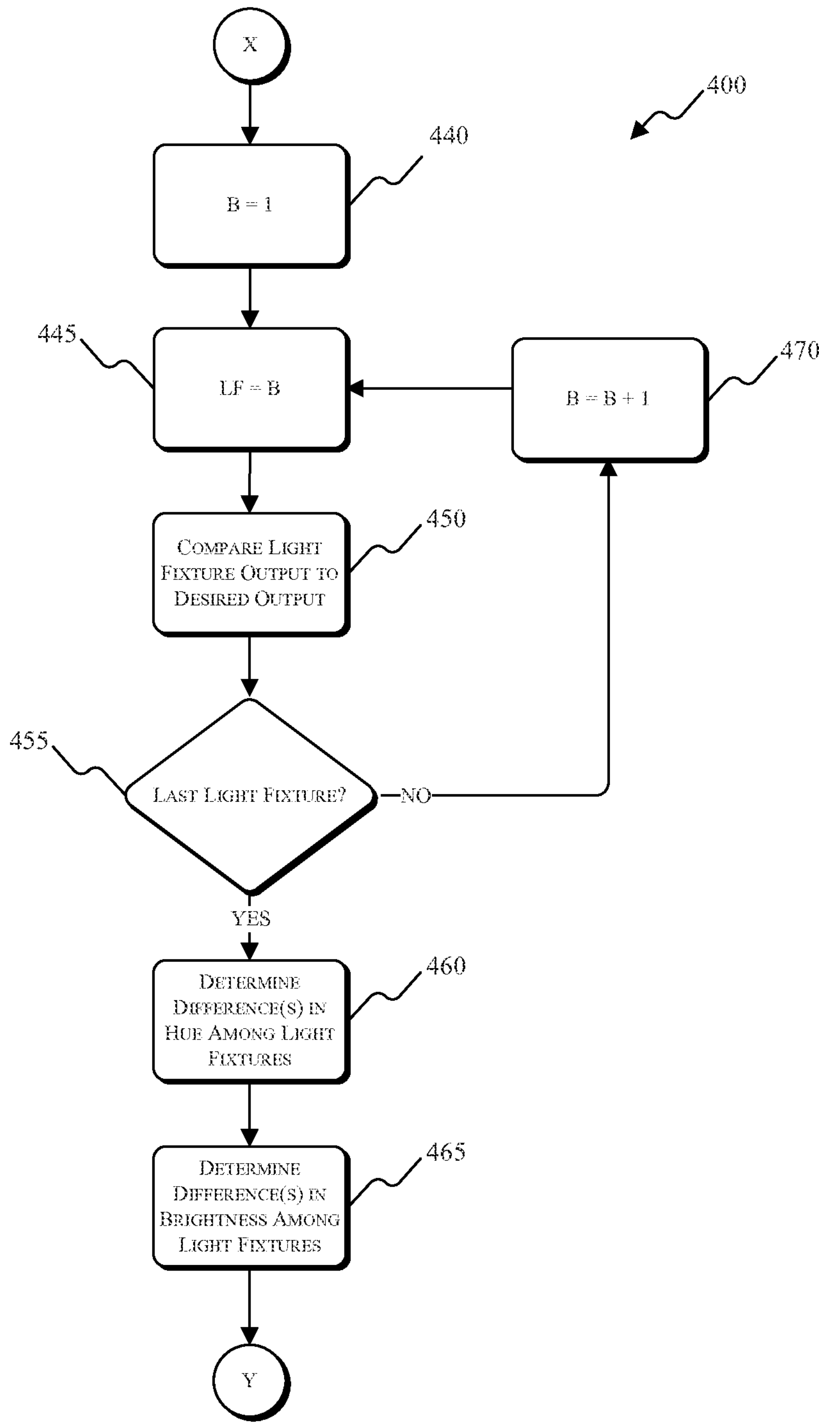

X
400
440
B = 1
445
LF = B
470
B = B + 1
450
COMPARE LIGHT FIXTURE OUTPUT TO DESIRED OUTPUT
455
LAST LIGHT FIXTURE?
NO
YES
460
DETERMINE DIFFERENCE(S) IN HUE AMONG LIGHT FIXTURES
465
DETERMINE DIFFERENCE(S) IN BRIGHTNESS AMONG LIGHT FIXTURES
Y

FIG. 6

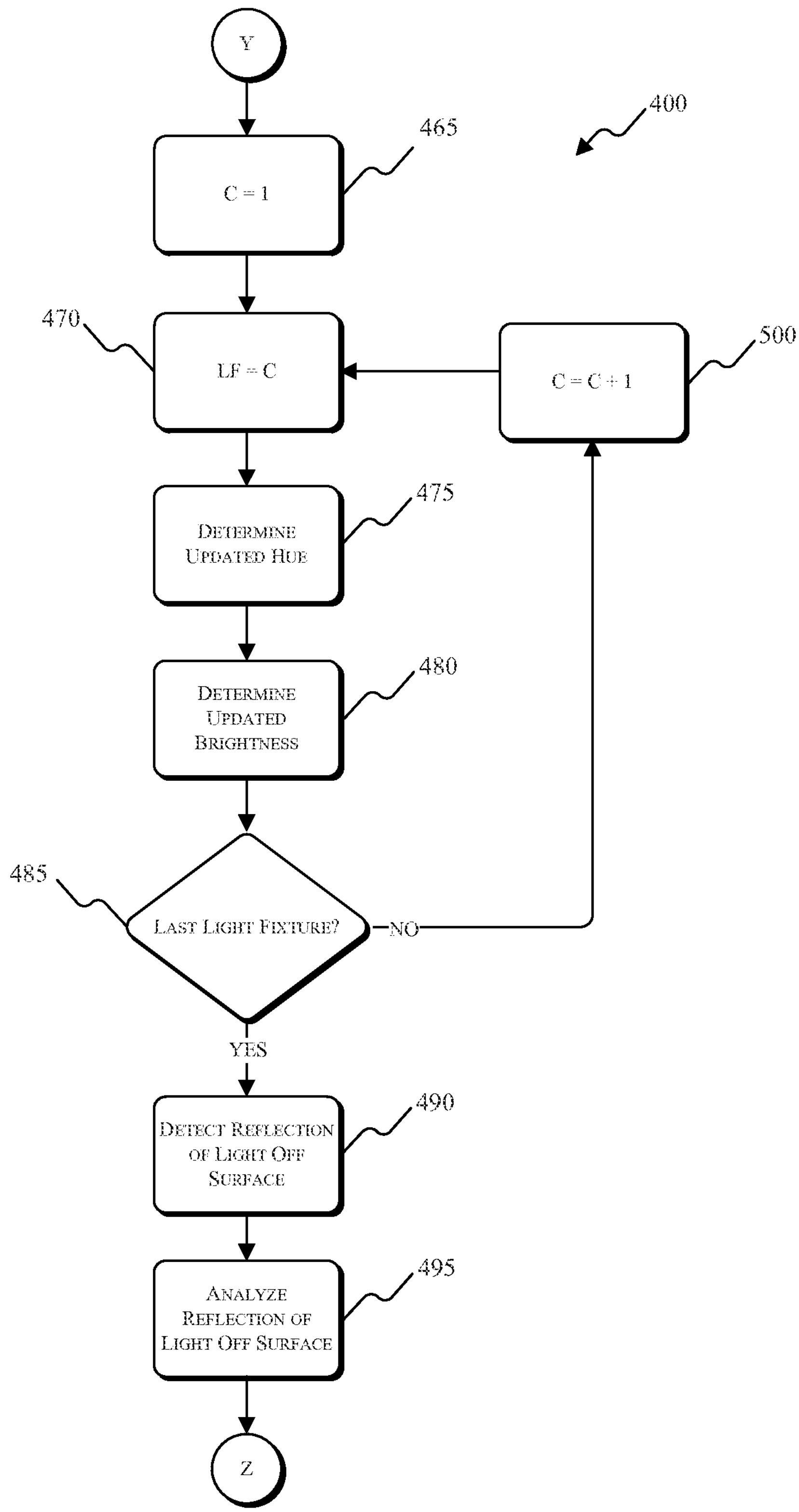
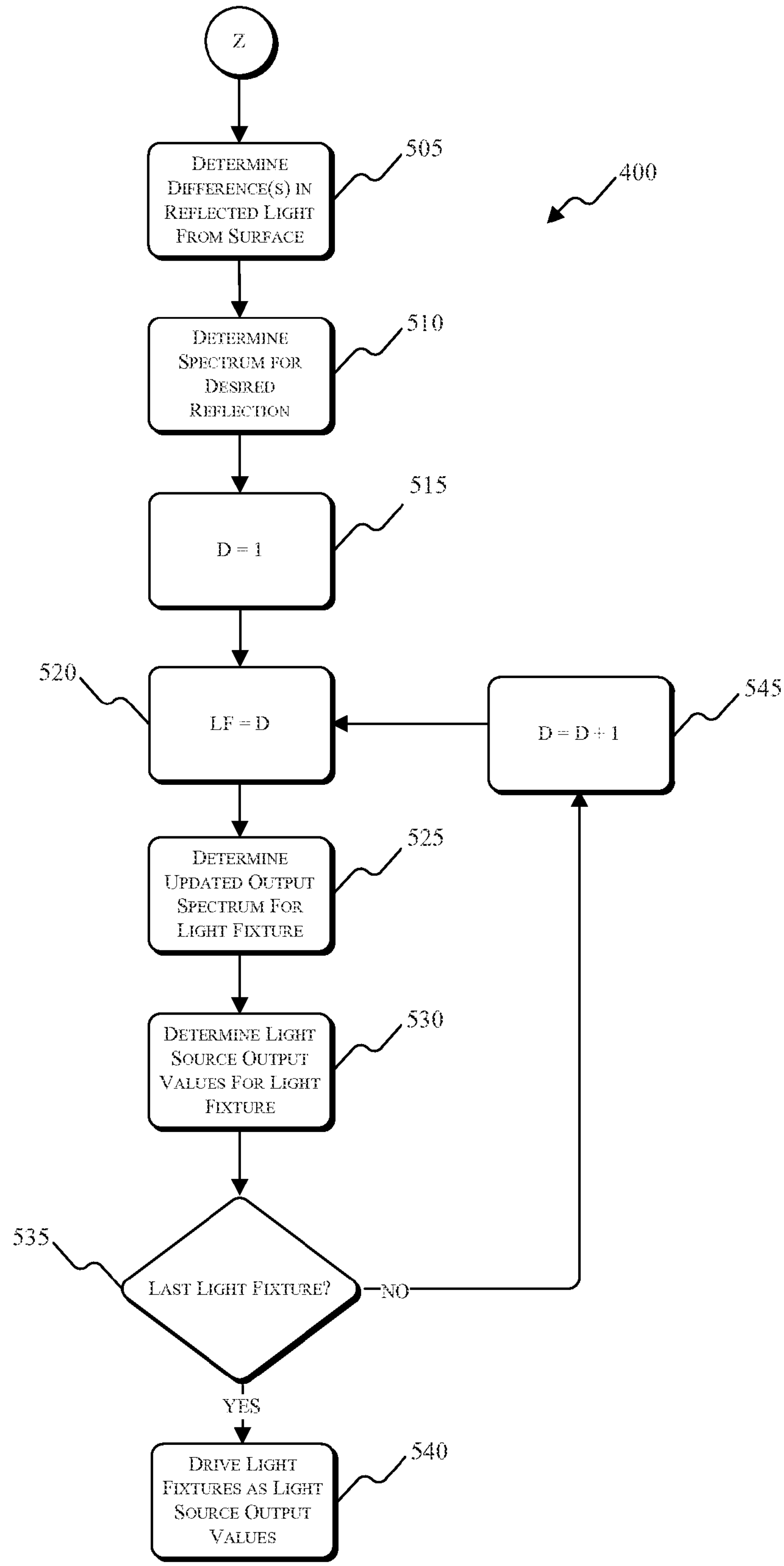

Y
400
465
C = 1
470
LF = C
500
C = C + 1
475
Determine Updated Hue
480
Determine Updated Brightness
485
Last Light Fixture?
NO
YES
490
Detect Reflection of Light Off Surface
495
Analyze Reflection of Light Off Surface
Z

FIG. 7


Z
DETERMINE DIFFERENCE(S) IN REFLECTED LIGHT FROM SURFACE
505
400
DETERMINE SPECTRUM FOR DESIRED REFLECTION
510
D = 1
515
LF = D
520
D = D + 1
545
DETERMINE UPDATED OUTPUT SPECTRUM FOR LIGHT FIXTURE
525
DETERMINE LIGHT SOURCE OUTPUT VALUES FOR LIGHT FIXTURE
530
LAST LIGHT FIXTURE?
535
NO
YES
DRIVE LIGHT FIXTURES AS LIGHT SOURCE OUTPUT VALUES
540

SYSTEM AND METHOD FOR CONTROLLING A PLURALITY OF LIGHT FIXTURE OUTPUTS

CROSS-REFERENCE TO RELATED APPLICATIONS

This application is a continuation of U.S. patent application Ser. No. 14/457,644, filed Aug. 12, 2014, now U.S. Pat. No. 9,144,140, the entire contents of which is incorporated herein by reference.

BACKGROUND

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

Among a plurality of light fixtures, each light fixture may generate a slightly different light output than the other light fixtures. Different light fixtures generate different light outputs for a variety of reasons. For example, one light fixture may include incandescent light sources and use gels to generate outputs of different colors, another light fixture may include four light-emitting diode ("LED") light sources, and a third light fixture may include seven LED light sources. Each of the light fixtures may be capable of producing outputs that are similar to one another, but different control settings may be required for each lighting fixture in order to produce a desired, consistent output among the light fixtures.

Additionally, as light sources age, the color output or color and the brightness of the light sources can be adversely affected. For example, as LEDs age, the brightness of the output generated for a given input setting may be lower than it was when the LEDs were new. These and other issues can adversely affect the appearance of the light produced by an individual light source or individual light fixture. Light sources or light fixtures that are only calibrated for color bin variances at the time of manufacturing are not compensated for these changes that occur over time.

SUMMARY

The above concerns are compounded when multiple light fixtures are implemented in the same venue and each light fixture may be generating a slightly or significantly different light output. Particular applications, such as theatre lighting which is highly sensitive to the manner in which light reflects off surfaces, are highly sensitive to inconsistencies in light output from both individual and plural light fixtures. In order to ensure that a lighting system is able to accurately and consistently produce a desired light output from venue to venue, the light fixtures within the system should be compensated for differences in light output among different light fixtures (e.g., due to age, type of fixture, etc.), as well as and based on light from the light fixtures that is reflected of one or more surfaces within the venue. As such, the invention provides systems and methods for controlling an output of a plurality of light fixtures of varying types such that the outputs of the light fixtures are consistent among the light fixtures and in order to produce the desired reflection of light off of a surface.

In one embodiment, the invention provides a method of controlling a plurality of light fixtures. The method includes detecting a first light output of a first light fixture, detecting a second light output of a second light fixture, and detecting a first reflection of light from a surface. The first light output has a first output color and a first output brightness. The first output color has a first output spectrum. The second light

output has a second output color and a second output brightness. The second output color has a second output spectrum. The first reflection of light corresponds to light from the first light fixture and the second light fixture that is reflected off of the surface. The method also includes analyzing the first light output to determine the first output color and the first output brightness, analyzing the second light output to determine the second output color and the second output brightness, and analyzing the first reflection of light to determine a spectrum of the light reflected off of the surface. The first light output is then compared to the second light output to determine a difference in color between the first light output and the second light output, the first output brightness is compared to the second output brightness to determine a difference in brightness between the first output brightness and the second output brightness, and the first reflection of light from the surface is compared to a desired reflection of light from the surface to determine a difference between the spectrum of the light reflected off of the surface and a desired spectrum of the light reflected off of light from the surface.

The method can also include calculating, when a difference in color between the first light output and the second light output is identified, an updated output color of at least one of the first light fixture and the second light fixture such that the output color of the first light output of the first light fixture substantially matches the output color of the second light output of the second light fixture. When a difference in brightness between the first output brightness and the second output brightness is identified, an updated output brightness for at least one of the first light fixture and the second light fixture is then calculated such that the output brightness of the first light output of the first light fixture substantially matches the output brightness of the second light output of the second light fixture. When a difference in the spectrum of the light reflected off of the surface and a desired spectrum of the light reflected off of the surface is identified, an updated output spectrum for at least one of the first light fixture and the second light fixture is calculated such that the first output spectrum substantially matches the second output spectrum without further changing the first output color, the second output color, the first output brightness, or the second output brightness. The method also includes determining a respective light source output value for each of the light sources in each of the first light fixture and the second light fixture such that the first output color substantially matches the second output color, the first output spectrum substantially matches the second output spectrum, and the first output brightness substantially matches the second output brightness. Each of the light sources in each of the first light fixture and the second light fixture is then driven at the respective light source output value.

In another embodiment, the invention provides a system for controlling the output of a plurality of light fixtures. The system includes a first light fixture including four or more light sources, a second light fixture including four or more light sources, a sensing module, and a controller. The sensing module is configured to detect a first light output of the first light fixture, detect a second light output of the second light fixture, and detect a first reflection of light from a surface. The first light output has a first output color and a first output brightness. The first output color has a first output spectrum. The second light output has a second output color and a second output brightness. The second output color has a second output spectrum. The first reflection of light corresponds to light from the first light fixture and the second light fixture that is reflected off of the surface.

The controller is configured to analyze the first light output to determine the first output color and the first output brightness, analyze the second light output to determine the second output color and the second output brightness, analyze the first reflection of light to determine a spectrum of the light reflected off of the surface, compare the first light output to the second light output to determine a difference in color between the first output color and the second output color, compare the first output brightness to the second output brightness to determine a difference in brightness between the first output brightness and the second output brightness, and compare the first reflection of light from the surface to a desired reflection of light from the surface to determine a difference between the spectrum of the light reflected off of the surface and a desired spectrum of the light reflected off of light from the surface.

The controller can also be configured to calculate an updated output color of at least one of the first light fixture and the second light fixture when a difference in color between the first light output and the second light output is identified such that the output color of the first light output of the first light fixture substantially matches the output color of the second light output of the second light fixture, calculate an updated output brightness for at least one of the first light fixture and the second light fixture when a difference in brightness between the first output brightness and the second output brightness is identified such that the output brightness of the first light output of the first light fixture substantially matches the output brightness of the second light output of the second light fixture, and calculate an updated output spectrum for at least one of the first light fixture and the second light fixture when a difference in the spectrum of the light reflected off of the surface and a desired spectrum of the light reflected off of light from the surface is identified such that the first output spectrum substantially matches the second output spectrum without further substantial change to the first output color, the second output color, the first output brightness, or the second output brightness. The controller then determines a respective light source output value for each of the four or more light sources in each of the first light fixture and the second light fixture such that the first output color substantially matches the second output color, the first output spectrum substantially matches the second output spectrum, and the first output brightness substantially matches the second output brightness. The controller then drives each of the four or more light sources in each of the first light fixture and the second light fixture at the respective light source output value.

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

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** illustrates a lighting system according to an embodiment of the invention.

FIG. **2** illustrates a lighting system controller 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. **4-7** are a process for controlling the output of a plurality of lighting fixtures.

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. Also, it is to be understood that the phraseology and terminology used herein is for the purpose of description and should not be regarded as limited. The use of "including," "comprising" or "having" and variations thereof herein is meant to encompass the items listed thereafter and equivalents thereof as well as additional items. The terms "mounted," "connected" and "coupled" are used broadly and encompass both direct and indirect mounting, connecting and coupling. Further, "connected" and "coupled" are not restricted to physical or mechanical connections or couplings, and can include electrical connections or couplings, whether direct or indirect. Also, electronic communications and notifications may be performed using any known means including direct connections, wireless connections, etc.

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 invention. Furthermore, and as described in subsequent paragraphs, the specific configurations illustrated in the drawings are intended to exemplify embodiments of the invention and that other alternative configurations are possible. The terms "processor," "central processing unit," and "CPU" are interchangeable unless otherwise stated. Where the terms "processor" or "central processing unit" or "CPU" are used as identifying a unit performing specific functions, it should be understood that, unless otherwise stated, those functions can be carried out by a single processor, or multiple processors arranged in multiple forms, including parallel processors, serial processors, tandem processors, or cloud processing/cloud computing configurations.

The invention described herein relates to systems, methods, devices, and computer readable media for controlling the outputs of a plurality of light fixtures. Each light fixture includes one or more light sources (e.g., incandescent light sources, LED light sources, etc.). A system that includes the light fixtures includes one or more controllers connected to or integral with the plurality of light fixtures that is/are configured to control the outputs of the plurality of light fixtures to maintain a consistent and desired output among the plurality of light fixtures. For example, different light sources generate light in different ways, and the performance of different light sources can gradually deteriorate in different ways and at different rates over time. As an illustrative example, an LED light fixture may gradually show a reduction in brightness or a shift in color as the LEDs age, even when a consistent input control is being provided. Additionally, some LEDs can exhibit such deterioration at different rates than other LEDs (e.g., based on the wavelength of light that the LEDs produce). As a result, when attempting to generate consistent outputs among the plurality of light fixtures, these differences for each individual light fixture must be corrected in order to produce an optimal output among the light fixtures. Further, the deterioration of the outputs of the light fixtures and the need to accurately and consistently control these outputs is heightened for applications that rely upon precise applications of color theory to produce a desired lighting effect, such as theatre lighting or lighting for similar venues. In some instances, the light that is reflected off of objects or surfaces is required to match a specific desired reflection of light off of that surface (e.g., a non-white background). If the outputs of the light fixtures have deteriorated, both the deterioration of the outputs of the light fixtures and the effect those changes have on the light reflected off of a surface should be compensated to ensure a consistent and accurate reflection of light.

In some implementations, light fixtures are used in, for example, a theatre, a hall, an auditorium, a studio, or the like. As illustrated in FIG. **1**, a lighting system **100** includes four light fixtures **105**, **110**, **115**, and **120**. Each of the light fixtures **105-120** is connected to a controller **125** in a wired or wireless manner for receiving control signals that control respective light outputs **130**, **135**, **140**, and **145** of the fixtures. The system **100** also includes a sensing module **150** that is configured to be capable of sensing the light output of one or more of the light fixtures **105-120**. In some constructions, the sensing module **150** senses the light output of one of the light fixtures **105-120** at a time. In other constructions, the sensing module **150** senses the light output of more than one of the light fixtures **105-120** at a time (e.g., two of the light fixtures **105-120**, each of the light fixtures **105-120**, etc.). The sensing module **150** is also configured to be capable of sensing the light **155** that is reflected off of a surface **160**. The light fixtures **105-120**, controller **125**, and sensing module **150** are described in more detail below. Because the light fixtures **105-120** can include four or more light sources (e.g., seven light sources), a desired output of the light fixture can, potentially, be achieved using a variety of different combinations of lights sources having different output intensity values. These combinations of light sources are known as metamers. Metamers correspond to the same color output or color of the light fixture but vary in spectral content. The spectral content of the output of the light fixture can be important, for example, when the output of the light fixture is illuminating an object or background that is not white. In such an instance, the user may determine that the output of the light fixture should include more or less of a particular light source (i.e., a color) in order to achieve a desired reflection of light off of the object.

FIG. **2** illustrates the system **100** in more detail. FIG. **2** illustrates the system **100** including the controller **125** that is operable to control the plurality of light fixtures **105-120**. In other constructions, each light fixture **105-120** can include its own controller. In such constructions, the controllers of the respective light fixtures are capable of communicating with one another or a central controller controls the individual light fixture controllers. For descriptive purposes, embodiments of the invention described herein are described with respect to a controller **125** that is operable to control each of the light fixtures **105-120**.

Specifically, the system **100** includes the controller **125**, the plurality of light fixtures **105-120**, the sensing module **150**, one or more indicators **165**, a power supply module **170**, and a user interface **175**. In some constructions, each light fixture **105-120** includes, for example, seven light sources (e.g., LEDs). Each light source is configured to generate light at a specific wavelength or range of wavelengths. For example, the light sources 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.). In other constructions, the light fixtures **105-120** can include incandescent light sources and a plurality of gels for creating desired color outputs. In other constructions, one or more of the light fixtures **105-120** include, 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 primarily described herein 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.

The controller **125** includes a plurality of electrical and electronic components that provide power, operational control, and protection to the components and modules within the system **100**. For example, the controller **125** includes, among other things, a processing unit **200** (e.g., a microprocessor, a microcontroller, or another suitable programmable device), a memory **205**, input units **210**, and output units **215**. The processing unit **200** includes, among other things, a control unit **220**, an arithmetic logic unit ("ALU") **225**, and a plurality of registers **230** (shown as a group of registers in FIG. **2**), and is implemented using a known computer architecture, such as a modified Harvard architecture, a von Neumann architecture, etc. The processing unit **200**, the memory **205**, the input units **210**, and the output units **215**, as well as the various modules connected to the controller **125** are connected by one or more control and/or data buses (e.g., common bus **235**). The control and/or data buses are shown generally in FIG. **2** for illustrative purposes. 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 invention described herein. In some embodiments, the controller **125** is implemented partially or entirely on a semiconductor (e.g., a field-programmable gate array ["FPGA"] semiconductor) chip.

The memory **205** 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 read-only memory ("ROM"), random access memory ("RAM") (e.g., dynamic RAM ["DRAM"], synchronous DRAM ["SDRAM"], etc.), electrically erasable programmable read-only memory ("EEPROM"), flash memory, a hard disk, an SD card, or other suitable magnetic, optical, physical, or electronic memory devices. The processing unit **200** is connected to the memory **205** and executes software instructions that are capable of being stored in a RAM of the memory **205** (e.g., during execution), a ROM of the memory **205** (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 system **100** can be stored in the memory **205** of the controller **125**. 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 **125** is configured to retrieve from memory and execute, among other things, instructions related to the control processes and methods described herein. For example, the controller **125** is configured to execute instructions retrieved from the memory **205** for generating necessary control signals for the light fixtures **105-120** that are required to drive the light sources of the light fixtures **105-120** to produce a desired color or consistent output. In other constructions, the controller **125** includes additional, fewer, or different components.

The sensing module **150** includes, for example, a spectroscope, spectrometer, a true color sensor, etc., for detecting and analyzing the light outputs of the light fixtures **105-120** and the light reflected off of a surface. In some embodiments, the sensing module **150** is used to analyze and enable control of the spectral power distribution ("SPD") of the plurality of light fixtures to match a SPD of a reference light source. The reference light fixture can be present at a venue and be used for a continuous comparison to one of the light fixtures **105-120**. Additionally or alternatively, the SPD of a desired reference light output can be stored in the memory **205** and retrieved from the memory **205** for the purpose of comparison to the detected light outputs of the light fixtures **105-120**. The sensing module **150** collects electromagnetic ("EM") radiation emitted from, for example, the light fixtures **105-120** as well as a reference light fixture. The sensing module **150** includes optics integrated with a set of light sensors, a controller (or the controller **125**), etc. In some constructions, the sensing module **150** enables a differential analysis of spectral features of radiation and analyzes spectroscopic data related to SPDs of the light fixtures **105-120** and the reference light fixture.

The user interface **175** is included to control the system **100** or the operation of an individual light fixture **105-120**. The user interface **175** is operably coupled to the controller **125** to control, for example, the output of the light fixtures **105-120**. The user interface **175** 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 **175** 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 **175** is separated from the system **100** and light fixtures **105-120**. The invention can also be implemented using a variety of color control methodologies, such as HSI, RGB, CYM, YIQ, YUV, HSV, HLS, XYS, etc. The input control techniques described herein are exemplary, and other input control techniques are within the spirit and scope of the invention. Additionally, the invention is capable of being implemented internal to or external from each of the light fixtures **105-120**. For example, the controller **125** includes sufficient memory and processing power to execute one or more programs associated with the inventive methods. Additionally or alternatively, each of the light fixtures **105-120** can include sufficient memory and processing power to execute one or more programs associated with the inventive methods.

The power supply module **170** supplies a nominal AC or DC voltage to the system **100** and/or light fixtures **105-120**. The power supply module **170** 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 **170** is also configured to supply lower voltages to operate circuits and components within the system **100**. Additionally or alternatively, the system **100** can receive power from one or more batteries or battery packs.

FIG. **3** illustrates the CIE xyY color space **300** and the available color gamut **305** for a light fixture. As such, only colors that fall within or on the illustrated color gamut **305** are reproducible by the light fixture. 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.

FIGS. **4-10** illustrate a process **400** for controlling the output of a plurality of light fixtures. Specifically, the process **400** is implemented to control the output of a plurality of light fixtures based on potential differences among the light fixtures, as well as based on the characteristics of the light that is reflected off one or more surfaces. The process **400** is used to provide a consistent light output (among the light fixtures) and an accurate reflection of light off of the one or more surfaces (with respect to a desired lighting effect). As such, the process **400** can be used to analyze and make consistent the light outputs of a plurality of light fixtures (e.g., LED light fixtures, incandescent light fixtures, etc.) and select a proper metamer to produce the desired lighting effect (e.g., reflection of light) for a given venue. The process **400** is shown as being executed by the controller **125** and performed in an iterative and serial manner. In some instances, the order in which steps are performed is provided for illustrative purposes and those steps may be executed in an order other than that provided in FIGS. **4-7** without affecting the results of the process **400**. For example, the step including the detection of the reflection of light off of a surface may be performed earlier in the process **400** than illustrated. Additionally, in some implementations, one or more of the illustrated steps may be combined or removed based on the particular application and needs for the process **400**. For example, in some implementations, new or updated values for output color, output brightness, and spectrum are determined at the same time, rather than individually and separately. Such an implementation may improve response times of the system **100** and reduce processing requirements when implementing the process **400**. For illustrative purposes, however, the steps of the process **400** are set forth in a more explicit and discrete manner.

The process **400** begins with light outputs from a plurality of light fixtures being generated (step **405**). At step **410**, a variable, A, is initialized to a value of 1 and a light fixture parameter, LF, is set equal to the variable, A, (step **415**). At step **420**, the light output from the light fixture, LF, is detected and then analyzed (step **425**). The light is analyzed to determine a variety of characteristics of the light. For example, the output of the light fixture can be analyzed to determine the color of the output of the light fixture, the brightness of the output of the light fixture, the spectrum of the output of the light fixture, etc. The results of this analysis can, for example, be stored in the memory **205** of the controller **125** for later use and/or comparison. If the light fixture, LF, is the last light fixture at step **430**, the process **400** proceeds to control section X shown in and described with respect to FIG. **5**. If, at step **430**, the light fixture, LF, is not the last light fixture, the variable, A, is incremented (step **435**) and the light fixture parameter, LF, is set equal to the incremented value of the variable, A, (step **415**). Steps **415-435** are performed until the light output of the last light fixture has been detected and analyzed. In some embodiments, the system includes two or more light fixtures. Additionally, although the process **400** is illustrated in a variety of instances with respect to incrementing a variable and executing specific steps for each iteration, such an iterative technique is provided for illustrative purposes. The invention is also capable of being implemented in such a way that incrementing a variable is not strictly required.

After the light output of the last light fixture has been detected and analyzed, the process **400** proceeds to step **440** in FIG. **5**. At step **440**, a variable, B, is initialized to a value of 1 and a light fixture parameter, LF, is then set equal to the variable, B, (step **445**). At step **450**, the light output of the light fixture, LF, is compared to a desired light output. The desired light output is associated with, for example, a control input from a user interface related to a desired color output (e.g., a CIE color space point, etc.) and a desired brightness output (e.g. a brightness percent, lumens, etc.) for the light fixture. Additionally or alternatively, the desired color output and the desired brightness output can be calculated or retrieved from a memory. The output color can then be compared to the desired color by directly comparing a determined CIE color point for the light output to a CIE color point for the desired color output. The output brightness can be compared to the desired brightness by comparing a desired lumen output with a determined lumen output for the light fixture. The comparisons may result in relative or absolute differences between the desired color or brightness and outputs of the light fixture that can be compensated as necessary to bring them into correspondence with one another, as described below.

If the light fixture, LF, is the last light fixture at step **455**, the controller **125** determines differences in color among the light outputs of the light fixtures (step **460**). It is possible that each of the light fixtures, LF, has a color that fails to correspond to the color of the desired light output. Alternatively, at least one of the light sources may have an output color that corresponds to the desired color. As a result, the number of light fixtures that may require compensation to correctly correspond to the desired color output may be all of the light fixtures or a subset of the light fixtures.

The differences in color (or brightness) among the light fixtures can be determined in a variety of ways. For example, determining differences among the light outputs of the light fixtures may include comparing each light output of each light fixture to every other light output of every other light fixture. Such a technique provides direct comparisons among the light outputs of the light fixtures. Additionally or alternatively, the light output of each light fixture can be compared to the desired light output for each light fixture. In such implementations, the relative differences among the light outputs of the light fixtures are determined with respect to the same reference value (i.e., the desired output). In implementations where both direct and relative differences among the light outputs of the light fixture are determined, the controller **125** can, for example, use the direct differences among the light outputs of the light fixtures to make all of the light outputs of the light fixtures consistent with the light output that was closest to the desired light output. The relative differences between that light output and the desired output can then be used to bring all of the light outputs of the light fixtures into correspondence with the desired light output.

The controller then determines differences in brightness among the light outputs of the light fixtures (step **465**). For example, it is possible that each of the light fixtures, LF, has a brightness that fails to correspond to the brightness of the desired light output. Alternatively, at least one of the light sources may have an output brightness that corresponds to the desired brightness. As a result, the number of light fixtures that may require compensation to correctly correspond to the desired brightness output may be all of the light fixtures or a subset of the light fixtures. The controller **125** uses the comparisons of the output brightnesses of the light fixtures to the desired output brightnesses to determine differences among the individual light fixtures as previously described.

If, at step **455**, the light fixture, LF, is not the last light fixture, the variable, B, is incremented (step **470**) and the light fixture parameter, LF, is set equal to the incremented value of the variable, B, (step **445**). Steps **445**-**455** are performed until the light output of the last light fixture has been compared to a desired light output.

Following step **465**, the process **400** proceeds to control section Y shown in and described with respect to FIG. **6**. At step **465**, a variable, C, is initialized to a value of 1 and a light fixture parameter, LF, is set equal to the variable, C, (step **470**). At step **475**, a new or updated value for the output color of the light fixture, LF, is determined. The updated value for the color is determined based on the comparison of the desired color output and the actual color output of the light fixture in step **450** and/or the determination of the differences among the light fixture color outputs at step **460**. In order to determine the new or updated color for the light fixture, a process similar to that disclosed in U.S. Pat. No. 8,384,294, entitled "SYSTEM AND METHOD FOR COLOR CREATION AND MATCHING", the entire content of which is hereby incorporated by reference, can be used. In some implementations, a simplex algorithm is used to find a best spectral and brightness match for a respective fixture. As a result, any difference between the actual output color and the desired output color that was determined to be present can be accurately compensated such that the light fixture, LF, produces the desired output color.

The controller then determines a new or updated value for the output brightness of the light fixture, LF, (step **480**). A similar procedure to that described above with respect to determining a new value for color can be used to determine a new value for brightness. In some embodiments, given a difference between the actual brightness output and the desired brightness output for the light fixture, the output of the light fixture can be normalized such that it produces the desired brightness. For example, if the brightness of the light fixture was supposed to have a value of 100% of full brightness, but instead had a value corresponding to 80% of full brightness, the brightness or output drive value settings for each light source in the light fixture could be increased by 20%. Such a modification substantially corrects the difference in brightness between the actual brightness output and the desired brightness output. If a desired brightness for the light fixture is not obtainable (e.g., the deterioration in brightness due to age cannot be overcome), the controller **125** can select a maximum possible percentage increase for all of the light sources in the light fixture and increase the brightness of each light source by that value to achieve the closest possible match to the desired brightness.

If the light fixture, LF, is the last light fixture at step **485**, the controller **125** detects the reflection of light off of one or more surfaces (step **490**), and analyzes the reflection of light off of the one or more surfaces (step **495**). The reflected light that is detected can be detected using the sensing module **150** described above such that the SPD of the reflected light can be analyzed. The reflected light that is detected can be analyzed, for example, by determining the constituent wavelengths of light that make up the reflected light and their respective spectral powers. The color of the surface for which light is reflecting off corresponds to the colors of light being produced by the light fixture that are not being absorbed by the surface. The results of this analysis can, for example, be stored in a memory of the controller **125** for later use and/or comparison. If, at step **485**, the light fixture, LF, is not the last light fixture, the variable, C, is incremented (step **500**) and the light fixture parameter, LF, is set equal to the incremented value of the variable, C, (step **470**). Steps **470**-**500** are performed until the light output of the last light fixture has been compared to a desired light output.

After the reflection of light off of the one or more surfaces has been analyzed, the process **400** proceeds to step **505** in

FIG. 7 where the controller 125 determines differences (if any) between the reflected light off of the one or more surfaces and an input or setting for the expected or desired reflection of light off of the one or more surfaces. As described above, when a plurality of light sources are present that produce substantially discrete wavelengths of light (e.g., four or more LEDs), it is possible to produce the same color output or color using a variety of different combinations of drive values for the light sources. Each of the different possible combinations of drive values for the light sources that produce the same color is known to those in the art as a metamer. Although the light output by the light fixture is independent of the metamer that is selected, the reflection of that light off of a surface that absorbs specific wavelength of light can vary significantly depending upon the selected metamer. As such, given the properties or characteristics of the surface (or object including the surface) for which light is being reflected, some light source colors that are used to generate the desired color may be emphasized more than others. The properties or characteristics of the surface can be entered by a user or retrieved from a memory. Similarly, a desired reflection of light off of the surface can be entered by a user or retrieved from a memory.

Based on the determination of any differences between the light reflected off of the one or more surfaces in step **505** and the expected or desired reflection of light, the controller **125** determines a new or updated spectrum of light (e.g., a metamer) that will more accurately and closely produce the desired reflection of light off of the one or more surfaces (step **510**). For example, using the properties or characteristics of the surface and a desired reflection of light off of the surface, the controller **125** can calculate or determine an approximate spectrum of light that properly emphasizes the wavelengths of light that are both reflected from and absorbed by the surface. In some embodiments, the spectrum can be retrieved from a memory (e.g., memory **205**). A process similar to that disclosed in U.S. Pat. No. 8,723,450, entitled "SYSTEM AND METHOD FOR CONTROLLING THE SPECTRAL CONTENT OF AN OUTPUT OF A LIGHT FIXTURE", the entire content of which is hereby incorporated by reference, can be used to select or control output spectrum. The new or updated spectrum of light for the light fixture is determined without further changing the output color or the output brightness of the light fixture.

At step **515**, a variable, D, is initialized to a value of 1 and a light fixture parameter, LF, is set equal to the variable, D, (step **520**). At step **525**, a new or updated target output spectrum for the light fixture, LF, is set or determined. The new or updated target output spectrum will correspond or substantially correspond to the spectrum determined at step **510**. In some embodiments, a light fixture may not be able to produce the desired spectrum determined at step **510**. For example, a seven color LED light fixture can produce more possible output colors and spectrums than a three or four color LED light fixture. As a result, when switching from venue to venue (each of which may include different types of light fixtures), the capabilities of the individual light fixtures may be limited. In the event that a light fixture is incapable of producing the desired output spectrum, the closest possible output spectrum that the light fixture can produce to the desired output spectrum will be set.

After the new or updated output spectrum for the fixture has been set for each light fixture, the controller **125** determines the light source drive values required to generate the new or updated output spectrum (step **530**). As described above, the updated color for each of the light fixtures was previously determined. However, given the aging of the light sources, and the manner in which aging affects different colors of light sources, any drive values that are ultimately required to produce a desired color, a desired brightness, and a desired spectrum of light may vary for each individual light fixture. As such, the light source drive values for each light fixture are calculated dependent in part upon the previously identified differences between the desired color output and the actual color output, the desired brightness and the actual brightness, and the desired spectrum.

If the light fixture, LF, is the last light fixture at step **535**, the controller **125** drives the light fixtures at the determined light source output values (step **540**). If, at step **535**, the light fixture, LF, is not the last light fixture, the variable, D, is incremented (step **545**) and the light fixture parameter, LF, is set equal to the incremented value of the variable, D, (step **520**). Steps **520-545** are performed the light source output values for each light fixture have been determined.

Thus, the invention provides, among other things, systems, methods, devices, and computer readable media for controlling the light output of a plurality of light fixtures in order to produce consistent and accurate light outputs among the light fixtures and a desired reflection of light off of one or more surfaces. Various features and advantages of the invention are set forth in the following claims.

What is claimed is:

1. A method of controlling a plurality of light fixtures, the method comprising:

determining a first light output of a first light fixture, the first light output having a first output color, the first output color having a first output spectrum;

determining a second light output of a second light fixture, the second light output having a second output color, the second output color having a second output spectrum;

detecting a first reflection of light from a surface, the first reflection of light corresponding to light from the first light fixture and the second light fixture that is reflected off of the surface;

analyzing the first reflection of light to determine a spectrum of the light reflected off of the surface;

determining a difference in color between the first light output and the second light output;

determining a difference between the spectrum of the light reflected off of the surface and a desired spectrum of the light reflected off of the surface;

when a difference in color between the first light output and the second light output is identified, calculating an updated output color of at least one of the first light fixture and the second light fixture such that the first output color substantially matches the second output color;

when a difference in the spectrum of the light reflected off of the surface and the desired spectrum of the light reflected off of the surface is identified, calculating an updated output spectrum for at least one of the first light fixture and the second light fixture such that the first output spectrum substantially matches the second output spectrum without further changing the first output color, or the second output color;

determining a respective light source output value for each light source in each of the first light fixture and the second light fixture such that the first output color substantially matches the second output color, the first output spectrum substantially matches the second output spectrum; and driving each of the light sources in each of the first light fixture and the second light fixture at the respective light source output value.

2. The method of claim 1, wherein the first light fixture include four or more light sources.

3. The method of claim 2, wherein the four or more light sources are light-emitting diodes ("LEDs").

4. The method of claim 1, wherein detecting the first light output, the second light output, and the first reflection of light includes detecting each using a spectrometer.

5. The method of claim 1, wherein determining a difference in color between the first light output and the second light output includes comparing the first output color and the second output color to a desired light output color.

6. The method of claim 5, wherein determining a difference in color between the first light output and the second light output further includes comparing the first output color to the second output color.

7. The method of claim 1, wherein determining a first light output of a first light fixture includes detecting the first light output of the first light fixture, and analyzing the first light output to determine the first output color.

8. The method of claim 1, wherein the first output color has a first output brightness and the second output color has a second output brightness, and wherein the method further comprises determining a difference in brightness between the first output brightness and the second output brightness, and when a difference in brightness between the first output brightness and the second output brightness is identified, calculating an updated output brightness for at least one of the first light fixture and the second light fixture such that the first output brightness substantially matches the second output brightness.

9. A system for controlling an output of a plurality of light fixtures, the system comprising:

a first light fixture including four or more light sources;

a second light fixture including four or more light sources;

a sensing module configured to

detect a first light output of the first light fixture, the first light output having a first output color, the first output color having a first output spectrum;

detect a second light output of a second light fixture, the second light output having a second output color, the second output color having a second output spectrum;

detect a first reflection of light from a surface, the first reflection of light corresponding to light from the first of the plurality of light fixtures and the second of the plurality of light fixtures that is reflected off of the surface; and

a controller configured to

analyze the first light output to determine the first output color,

analyze the first reflection of light to determine a spectrum of the light reflected off of the surface,

determine a difference in color between the first light output and the second light output,

determine a difference between the spectrum of the light reflected off of the surface and a desired spectrum of the light reflected off of the surface,

calculate an updated output color of at least one of the first light fixture and the second light fixture when a difference in color between the first light output and the second light output is identified such that the output color of the first light output of the first light fixture substantially matches the output color of the second light output of the second light fixture,

calculate an updated output spectrum for at least one of the first light fixture and the second light fixture when a difference in the spectrum of the light reflected off of the surface and the desired spectrum of the light reflected off of the surface is identified such that the first output spectrum substantially matches the second output spectrum without further changing the first output color, or the second output color,

determine a respective light source output value for each of the four or more light sources in each of the first light fixture and the second light fixture such that the first output color substantially matches the second output color, and the first output spectrum substantially matches the second output spectrum, and

drive each of the four or more light sources in each of the first light fixture and the second light fixture at the respective light source output value.

10. The system of claim 9, wherein the first of the plurality of light fixtures includes seven light sources.

11. The system of claim 9, wherein the four or more light sources are light-emitting diodes ("LEDs").

12. The system of claim 9, wherein the sensing module includes a spectrometer.

13. The system of claim 9, wherein the controller is further configured to compare the first output color and the second output color to a desired light output color.

14. The system of claim 13, wherein the controller is further configured to compare the first output color to the second output color.

15. The system of claim 9, further comprising a third light fixture including four or more light sources.

16. The system of claim 15, wherein the sensing module is further configured to

detect a third light output of the third light fixture, the third light output having a third output color , the third output color having a third output spectrum; and

the controller is further configured to

analyze the third light output to determine the third output color,

determine a difference in color between the first light output, the second light output, and the third light output,

calculate an updated output color of at least one of the first light fixture, the second light fixture, and the third light fixture when a difference in color among the first light output, the second light output, and the third light output is identified such that the output color of the first light output of the first light fixture substantially matches the output color of the second light output of the second light fixture and the output color of the third light output of the third light fixture,

calculate an updated output spectrum for at least one of the first light fixture, the second light fixture, and the third light fixture when a difference in the spectrum of the light reflected off of the surface and a desired spectrum of the light reflected off of the surface is identified such that the first output spectrum substantially matches the second output spectrum and the third output spectrum without further changing the first output color, the second output color, or the third output color,

determine a respective light source output value for each of the four or more light sources in each of the first light fixture, the second light fixture, and the third light fixture such that the first output color substantially matches the second output color and the third output color, and the first output spectrum substantially matches the second output spectrum and the third output spectrum, and

drive each of the four or more light sources in each of the first light fixture, the second light fixture, and the third light fixture at the respective light source output value.

17. A controller for a lighting system, the controller comprising:

a processor and a computer readable medium, the computer readable medium including executable instructions capable of being retrieved from the medium and executed by the processor to cause the controller to

analyze a first light output from a first light fixture to determine a first output color,

analyze a second light output from a second light fixture to determine a second output color,

analyze a first reflection of light from a surface to determine a spectrum of the light reflected off of the surface,

determine a difference in color between the first light output and the second light output,

determine a difference between the spectrum of the light reflected off of the surface and a desired spectrum of the light reflected off of the surface,

calculate, when a difference in color between the first light output and the second light output is identified, an updated output color of at least one of the first light fixture and the second light fixture such that the first output color substantially matches the second output color,

calculate, when a difference in the spectrum of the light reflected off of the surface and the desired spectrum of the light reflected off of light from the surface is identified, an updated output spectrum for at least one of the first light fixture and the second light fixture such that the spectrum substantially matches the desired spectrum without further changing the first output color, or the second output color,

determine a respective light source output value for each light source in each of the first light fixture and the second light fixture such that the first output color substantially matches the second output color, and the spectrum substantially matches the desired spectrum, and

drive each of the light sources in each of the first light fixture and the second light fixture at the respective light source output value.

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