APPARATUSES, SYSTEMS, AND METHODS FOR CALIBRATING DISPLAYS

Anonymous Anonymous

Follow this and additional works at: https://www.tdcommons.org/dpubs_series

Recommended Citation
https://www.tdcommons.org/dpubs_series/3222

This work is licensed under a Creative Commons Attribution 4.0 License.
This Article is brought to you for free and open access by Technical Disclosure Commons. It has been accepted for inclusion in Defensive Publications Series by an authorized administrator of Technical Disclosure Commons.
APPARATUSES, SYSTEMS, AND METHODS FOR CALIBRATING DISPLAYS

BACKGROUND

[0001] High-definition displays are increasingly used in a variety of applications, including televisions, personal computers, smartphones, tablets, camera viewfinders, and even virtual reality headsets. High-definition displays commonly include numerous pixels having different color pixel elements (e.g., red, green, and blue sub-pixels) that are independently driven to produce detailed color images that are visible to users. Displays are typically calibrated so that users properly perceive the intended image colors in the displayed images. To accomplish this, calibration systems may obtain image information from displays in order to identify and apply light-output adjustments to pixel elements of the displays.

[0002] Conventional calibration systems, however, are often incapable of adequately calibrating the ever-improving and increasing specifications and demands of high-definition displays. For example, because virtual reality headsets often utilize multiple separate displays that are viewed simultaneously by a user, any inconsistencies in the calibration of these separate displays may result in the user perceiving noticeably different color spectrums in the displays, potentially souring the user’s virtual reality experience. Calibration systems for performing high-accuracy calibration of displays are often very costly and time-consuming. Accordingly, it is often difficult or time- or cost-prohibitive to perform real-time calibration of entire displays using high-accuracy light measurement tools.

SUMMARY

[0003] As will be described in greater detail below, the instant disclosure describes various improved apparatuses, systems, and methods for calibrating displays. In one example, a...
display calibration apparatus may include a (i) spectrometry device positioned to capture light emitted by a group of sub-pixels in a sub-region of a display that is both (a) located within a light-emitting region of the display and (b) smaller than the light-emitting region and (ii) at least one camera device positioned to capture light emitted by a plurality of sub-pixels, in the light-emitting region of the display, that includes the group of sub-pixels.

[0004] In some examples, the camera device may include a plurality of camera devices, each of which may capture light components having wavelengths within a different range of wavelengths. In these examples, each of the camera devices may capture light components having wavelengths within a red wavelength range, a blue wavelength range, and/or a green wavelength range. In addition, each of the camera devices may include a separate wavelength filter that blocks the passage of light components having wavelengths outside its corresponding range of wavelengths.

[0005] In one embodiment, the spectrometry device may generate spectrum light information based on the light emitted by the group of sub-pixels in the sub-region of the display and the camera device(s) may generate image light information based on the light emitted by the plurality of sub-pixels in the light-emitting region of the display. In this embodiment, the spectrometry device may generate the spectrum light information by measuring wavelengths and intensities of light components of the light emitted by the group of sub-pixels in the sub-region of the display. In one example, the display calibration apparatus may also include (i) a support body that is coupled to the spectrometry device and the camera and (ii) a display mounting member for mounting the display so that the light-emitting region faces the spectrometry device and the camera(s).
[0006] A corresponding display calibration system may include (i) a spectrometry device positioned to capture light emitted by a group of sub-pixels in a sub-region of a display that is both (a) located within a light-emitting region of the display and (b) smaller than the light-emitting region, (ii) at least one camera device positioned to capture light emitted by a plurality of sub-pixels, in the light-emitting region of the display, that include the group of sub-pixels, and (iii) a calibration computing device that is (a) communicatively coupled to the spectrometry device and the camera device and that (b) generates calibration data for driving the plurality of sub-pixels in the light-emitting region of the display based on information received from the spectrometry device and the camera device.

[0007] In some examples, (i) the spectrometry device may obtain spectrum light information from the captured light emitted by the group of sub-pixels in the sub-region of the display, (ii) the camera device(s) may obtain image light information from the captured light emitted by the plurality of sub-pixels in the light-emitting region of the display, (iii) the calibration computing device may receive the spectrum light information from the spectrometry device and the image light information from the camera device(s), and (iv) the calibration computing device may generate the calibration data for driving the plurality of sub-pixels in the light-emitting region of the display based on the spectrum light information and the image light information. In addition, the camera device may include a plurality of camera devices, each of which may capture light components having wavelengths within a different range of wavelengths.

[0008] Similarly, a corresponding method may include (i) driving a plurality of sub-pixels in a light-emitting region of a display, (ii) receiving, from a spectrometry device, spectrum light information obtained from light emitted by a group of sub-pixels of the plurality of sub-
pixels in a sub-region of the display that is both (a) located within the light-emitting region of the display and (b) is smaller than the light-emitting region, (iii) receiving, from at least one camera device, image light information obtained from light emitted by the plurality of sub-pixels in the light-emitting region of the display, and (iv) generating calibration data for driving the plurality of sub-pixels in the light-emitting region of the display based on the spectrum light information and the image light information.

[0009] In some examples, generating the calibration data for driving the plurality of sub-pixels may include correlating the image light information received from the camera device(s) with at least a portion of the spectrum light information received from the spectrometry device. In addition, generating the calibration data for driving the plurality of sub-pixels may include generating a correction factor for driving at least one sub-pixel of the plurality of sub-pixels in the light-emitting region of the display.

[0010] In one example, receiving the image light information obtained from the light emitted by the plurality of sub-pixels in the light-emitting region of the display may include receiving, from a plurality of camera devices, a plurality of sets of image light information obtained from the light emitted by the plurality of sub-pixels in the light-emitting region of the display. In this example, each of the plurality of sets of image light information may correspond to a different range of light wavelengths.

[0011] In one embodiment, the method may also include driving, utilizing the calibration data, the plurality of sub-pixels in the light-emitting region of the display. In this embodiment, the method may also include (i) receiving, from the spectrometry device, additional spectrum light information obtained from additional light emitted by the group of sub-pixels or
another group of sub-pixels in the light-emitting region of the display and/or (ii) receiving, from the camera device(s), additional image light information obtained from additional light emitted by the plurality of sub-pixels in the light-emitting region of the display.

[0012] In addition, the method may include determining, based on the additional spectrum light information and/or the additional image light information, whether the display is calibrated to a specified degree when the plurality of sub-pixels in the light-emitting region of the display are driven utilizing the calibration data. The method may also include generating modified calibration data for driving the plurality of sub-pixels in the light-emitting region of the display based on the additional spectrum light information and/or the additional image light information. In one example, driving the plurality of sub-pixels in the light-emitting region of the display may include driving two or more sub-pixels of the plurality of sub-pixels to emit light having different intensities.

[0013] Features from any of the above-mentioned embodiments may be used in combination with one another in accordance with the general principles described herein. These and other embodiments, features, and advantages will be more fully understood upon reading the following detailed description in conjunction with the accompanying drawings and claims.

BRIEF DESCRIPTION OF THE DRAWINGS

[0014] The accompanying drawings illustrate a number of exemplary embodiments and are a part of the specification. Together with the following description, these drawings demonstrate and explain various principles of the instant disclosure.
[0015] FIG. 1 is a perspective view of an exemplary head-mounted-display system in accordance with some embodiments.

[0016] FIGS. 2A and 2B are views of an exemplary display in accordance with some embodiments.

[0017] FIG. 3 is a block diagram of an exemplary electronic display device in accordance with some embodiments.

[0018] FIG. 4 is a perspective view of an exemplary apparatus for calibrating displays in accordance with some embodiments.

[0019] FIG. 5 is a perspective view of an exemplary apparatus for calibrating displays in accordance with some embodiments.

[0020] FIG. 6 is a block diagram of an exemplary system for calibrating displays in accordance with some embodiments.

[0021] FIG. 7 is a flow diagram of an exemplary method for calibrating displays in accordance with some embodiments.

[0022] FIG. 8 shows an exemplary chromaticity diagram utilized for calibrating displays in accordance with some embodiments.

[0023] FIG. 9 is a block diagram of an exemplary system for calibrating displays in accordance with some embodiments.

[0024] Throughout the drawings, identical reference characters and descriptions indicate similar, but not necessarily identical, elements. While the exemplary embodiments described herein are susceptible to various modifications and alternative forms, specific embodiments have been shown by way of example in the drawings and will be described in detail
herein. However, the exemplary embodiments described herein are not intended to be limited to the particular forms disclosed. Rather, the instant disclosure covers all modifications, equivalents, and alternatives falling within the scope of the appended claims.

**DETAILED DESCRIPTION OF EXEMPLARY EMBODIMENTS**

**[0025]** The present disclosure is generally directed to apparatuses, systems, and methods for calibrating displays. As will be explained in greater detail below, embodiments of the instant disclosure may include a spectrometry device utilized in conjunction with at least one camera device. The camera device(s) may include, for example, a plurality of color-specific cameras that each capture separate color components of light. The spectrometry device may obtain detailed spectrum light information based on light emitted by pixels located within a sub-region of a display that is smaller than a total light-emitting region of the display. In addition, the camera device(s) may obtain image light information from based on light emitted by light-emitting region of the display, including light emitted by portions of the display outside the sub-region.

**[0026]** The spectrum light information obtained by the spectrometry device may be correlated with the image light information obtained by the camera device(s) to more accurately analyze the light emitted by the pixels of the display for purposes of calibrating the pixels. For example, the detailed spectrum light information obtained by the spectrometer from the portion of the display in the sub-region may be used to interpret the light information obtained by the camera device(s) from the entire light-emitting region of the display, a small portion of which includes the sub-region. By correlating the spectrum light information from the sub-region of the display with the image light information for the entire display obtained by the camera device(s),
an accurate picture of the colors emitted by the display may be obtained without the expense required to obtain spectrometry information for the entire light-emitting region of the display using a spectrometry device. Additionally, because the spectrum light information may be obtained from the sub-region concurrent with obtaining the image light information for the entire display, data may be analyzed and calibration of the display may be performed in real-time.

[0027] The following will provide, with reference to FIGS. 1-3, detailed descriptions of displays that may be calibrated using the apparatuses, systems, and methods described herein. In addition, the discussion corresponding to FIGS. 4-9 will provide examples of apparatuses, systems, and methods for calibrating displays.

[0028] FIG. 1 is a perspective view of a head-mounted-display system 100 in accordance with some embodiments. In some embodiments, head-mounted-display system 100 may include a head-mounted-display device 102, audio subsystems 104, a strap assembly 106, and a facial-interface system 108. The term “head-mounted-display device,” as used herein, generally refers to any type or form of display device or system that is worn on or about a user’s head and displays visual content to the user. Head-mounted-display devices may display content in any suitable manner, including via a screen (e.g., an LCD or LED screen), a projector, a cathode ray tube, an optical mixer, etc. Head-mounted-display devices may display content in one or more of various media formats. For example, a head-mounted-display device may display video, photos, and/or computer-generated imagery (CGI). Head-mounted-display device 102 may include a head-mounted-display housing 116 surrounding various components of head-
mounted-display device 102, including lenses 114 and various electronic components, including display components as described above.

[0029] Head-mounted-display devices may provide diverse and distinctive user experiences. Some head-mounted-display devices may provide virtual-reality experiences (i.e., they may display computer-generated or pre-recorded content), while other head-mounted-display devices may provide real-world experiences (i.e., they may display live imagery from the physical world). Head-mounted-display devices may also provide any mixture of live and virtual content. For example, virtual content may be projected onto the physical world (e.g., via optical or video see-through), which may result in augmented reality or mixed reality experiences. Head-mounted-display devices may be configured to be mounted to a user’s head in a number of ways. Some head-mounted-display devices may be incorporated into glasses or visors. Other head-mounted-display devices may be incorporated into helmets, hats, or other headwear.

[0030] In some embodiments, audio subsystems 104 may be integrated with head-mounted-display device 102 and may provide audio signals to the user’s ears. Head-mounted-display system 100 may, for example, have two audio subsystems 104 located on the left and right sides of head-mounted-display system 100 to provide audio signals to the user’s left and right ears, as shown in FIG. 1.

[0031] Strap assembly 106 may be used for adjustably mounting head-mounted-display device 102 on the user’s head. As shown in FIG. 1, strap assembly 106 may include various straps, such as an upper strap and lower straps, that are coupled to head-mounted-display device 102 to adjustably conform to the top and/or sides of the user’s head when the user is wearing head-mounted-display device 102.
In some embodiments, facial-interface system 108 may be configured to comfortably rest against a region of the user’s face, including a region surrounding the user’s eyes, when head-mounted-display system 100 is worn by the user. In these embodiments, facial-interface system 108 may include a facial interface 110 that contacts selected regions of the user’s face. Facial interface 110 may surround a viewing region 112 that includes the user’s field of vision while the user is wearing head-mounted-display system 100, allowing the user to look through lenses 114 of head-mounted-display device 102 without interference from outside light while the user is wearing head-mounted-display system 100. Displays (see, e.g., display 120 shown in FIG. 2A) disposed within head-mounted-display housing 116 may be visible to the user through lenses 114. For example, a separate display may be respectively visible to a user through each of lenses 114. The separate displays may each display separate images to each of the user’s eyes to together produce images that may be interpreted by the user as three-dimensional images.

FIG. 2A shows an exemplary display 120, such as a display that may be utilized in head-mounted-display system 100 shown in FIG. 1. Additionally or alternatively, display 120 may be a display that is configured for use in any suitable electronic display device, without limitation. For example, display 120 may be a display for use in a television, a computer monitor, a laptop monitor, a tablet device, a portable device, such as a cellular telephone (e.g., a smartphone), a wrist-watch device, a pendant device or other wearable or miniature device, a media player, a camera viewfinder, a gaming device, a navigation device, and/or any other type of device including an electronic display, without limitation.
Display 120 may include a plurality of pixels and subpixels that form visible images according to any suitable display technology. For example, display 120 may include image pixels formed of light-emitting diodes (LEDs), organic light-emitting diodes (OLEDs), plasma cells, electrophoretic display elements, liquid crystal display (LCD) components, electrowetting display elements, cathode ray tube (CRT elements), and/or any other suitable image pixel technology. Display 120 may also include a light-emitting region 122 that includes a plurality of sub-pixels that are individually driven by an active matrix of thin-film transistors to form an image that is visible to the human eye. Light may be emitted from a display surface 124 of display 120 such that the images are visible to a user viewing display surface 124. In some examples, images may be produced by driving sub-pixels at different currents and/or voltages such that different amounts of light are emitted from each of the sub-pixels. Various visible colors may be produced by combining different amounts of emitted light from adjacent sub-pixels of different colors (e.g., red, green, and/or blue sub-pixels) such that a user perceives colors corresponding to the combinations of sub-pixels.

FIG. 2B illustrates a portion of display 120, which is magnified to show individual sub-pixel elements of display 120 within sub-region 126. As will be described in greater detail below, sub-region 126 may correspond to an area or at least a portion of an area of display 120 from which a spectrometry device receives light. Display 120 may include various sub-pixels that each emit light having a specified wavelength and/or range of wavelengths. For example, display 120 may include red, green, and/or blue sub-pixel elements that respectively emit red, green, and/or blue light. Additionally or alternatively, display 120 may include sub-pixels that emit any other suitable visible light colors, including, for example, cyan and/or magenta light. For
example, FIG. 2B illustrates a plurality of sub-pixels 128A, a plurality of sub-pixels 128B, and a plurality of sub-pixels 128C. In some embodiments, each of sub-pixels 128A may emit light having a first wavelength and/or range of wavelengths (e.g., blue light), each of sub-pixels 128B may emit light having a second wavelength and/or range of wavelengths (e.g., green light), and each of sub-pixels 128C may emit light having a third wavelength and/or range of wavelengths (e.g., red light). Each pixel of display 120 may include at least one sub-pixel 128A, sub-pixel 128B, and sub-pixel 128C. In some examples, each pixel may include more than one sub-pixel 128A, sub-pixel 128B, and/or sub-pixel 128C.

[0036] According to at least one example, sub-pixel 128A, sub-pixel 128B, and/or sub-pixel 128C may include individual light-emitting elements, such as organic light-emitting diodes, that emit light having specified colors when a current is passed through the light-emitting elements. The amount of light emitted from each of sub-pixel 128A, sub-pixel 128B, and sub-pixel 128C may be controlled by controlling an amount of current passed through each of the light-emitting elements. Additionally or alternatively, at least a portion of display 120 may be backlit (e.g., by a light source, such as a light-emitting diode light source) and sub-pixel 128A, sub-pixel 128B, and/or sub-pixel 128C may include color filters that allow passage of light having different wavelengths and/or ranges of wavelengths. In such an example, the amount of light emitted from each of sub-pixel 128A, sub-pixel 128B, and sub-pixel 128C may be controlled by a light-blocking layer, such as a liquid crystal layer, that adjusts an amount of light that passes through each of the color filters from a back-light source. The amount of light passing through each of sub-pixel 128A, sub-pixel 128B, and sub-pixel 128C may be controlled by controlling an
amount of voltage applied to light-blocking elements of the light-blocking layer corresponding to each of sub-pixel 128A, sub-pixel 128B, and sub-pixel 128C.

[0037] FIG. 3 illustrates an exemplary display subsystem 130 that may be utilized in and/or in conjunction with a display device, such as head-mounted-display device 102 shown in FIG. 1. As shown in FIG. 3, display subsystem 130 may include display 120 and a display computing device 131 for controlling display 120. In some embodiments, display subsystem 130 may include a plurality of displays, such as a pair of displays utilized in head-mounted-display device 102. For example, head-mounted-display device 102 may include a pair of displays 120 that are each controlled by a separate display computing device 131. Additionally or alternatively, a pair of displays 120 of head-mounted-display device 102 may both be controlled by a single display computing device 131.

[0038] According to at least one embodiment, display computing device 131 may include a display driver 140 for driving sub-pixels of display 120. Display driver 140 may include any suitable circuitry for driving display 120. For example, display driver 140 may include at least one integrated circuit (IC). In some examples, display driver 140 may include timing controller (TCON) circuitry that receives image signals and generates horizontal and vertical timing signals for display 120. Display driver 140 may, for example, be mounted on an edge of a thin-film-transistor (TFT) substrate layer of display 120.

[0039] Display subsystem 130 may also include one or more modules 132 for performing one or more display tasks. As will be explained in greater detail below, display subsystem 130 may include a graphics control module 134 that provides display data and control signals to display driver 140 for producing images on display 120. Graphics control module 134
may include, for example, a video card and/or video adapter that is used to provide video data and/or display control signals to display 120. In some examples, video data may include text, graphics, images, moving video content, and/or any other suitable image content to be presented on display 120.

[0040] In at least one embodiment, display subsystem 130 may include a calibration data module 136 that stores and utilizes calibration data for display 120. For example, calibration data module 136 may include calibration data, such as correction factors, that are applied to video data utilized by display driver 140 to produce calibrated images on display 120. As will be described in greater detail below, such calibration data may be generated by a display calibration system based on image light data obtained from light emitted by sub-pixels of display 120.

[0041] Additionally, display subsystem 130 may include a communication module 138 that receives video data and calibration data from one or more computing devices. For example, communication module 138 may receive video data to be displayed on display 120 from any suitable video and/or image source. Communication module 138 may also, for example, receive calibration data from a display calibration system. In some examples, communication module 138 may also receive user input supplied by a user via an input-output device (e.g., touch screens, buttons, joysticks, click wheels, scrolling wheels, touch pads, key pads, keyboards, microphones, speakers, tone generators, position and/or orientation sensors, vibrators, cameras, sensors, light-emitting diodes and/or other status indicators, data ports, etc.) to display subsystem 130. In at least one example, communication module 138 may also send data from display subsystem 130 to external devices and/or to a user.
[0042] Display calibration information may be loaded onto display subsystem 130 during and/or following manufacturing. For example, as will be described in greater detail below, correction factors, such as color, illumination intensity, and/or location-specific correction factors may be generated and stored on display subsystem 130. Such stored correction factors may be accessed during operation of display 120 to produce calibrated images for a user. For example, incoming video data including sub-pixel values for display 120 may be received by communication module 138 and calibration data module 136 may, based on the received sub-pixel values, calculate and apply appropriate correction factors to the sub-pixel values to obtain adapted sub-pixel values.

[0043] In certain embodiments, one or more of modules 132 in FIG. 3 may represent one or more software applications or programs that, when executed by a computing device, may cause the computing device to perform one or more tasks. For example, and as will be described in greater detail below, one or more of modules 132 may represent modules stored and configured to run on one or more computing devices (e.g., head-mounted-display device 102 shown in FIG. 1 and/or the computing devices shown in FIGS. 3 and 5). One or more of modules 132 in FIG. 1 may also represent all or portions of one or more special-purpose computers configured to perform one or more tasks.

[0044] As illustrated in FIG. 3, example display subsystem 130 may also include one or more memory devices, such as memory 142. Memory 142 generally represents any type or form of volatile or non-volatile storage device or medium capable of storing data and/or computer-readable instructions. In one example, memory 142 may store, load, and/or maintain one or more of modules 132. Examples of memory 142 include, without limitation, Random
Access Memory (RAM), Read Only Memory (ROM), flash memory, Hard Disk Drives (HDDs), Solid-State Drives (SSDs), optical disk drives, caches, variations or combinations of one or more of the same, and/or any other suitable storage memory.

[0045] As illustrated in FIG. 3, example display subsystem 130 may also include one or more physical processors, such as physical processor 144. Physical processor 144 generally represents any type or form of hardware-implemented processing unit capable of interpreting and/or executing computer-readable instructions. In one example, physical processor 144 may access and/or modify one or more of modules 132 stored in memory 142. Additionally or alternatively, physical processor 144 may execute one or more of modules 132 to facilitate calibration of display 120. Examples of physical processor 144 include, without limitation, microprocessors, microcontrollers, Central Processing Units (CPUs), Field-Programmable Gate Arrays (FPGAs) that implement softcore processors, Application-Specific Integrated Circuits (ASICs), portions of one or more of the same, variations or combinations of one or more of the same, and/or any other suitable physical processor.

[0046] FIG. 4 shows an exemplary light measurement subsystem 150 for calibrating a display, such as display 120 shown in FIGS. 2A, 2B, and 3. As shown in FIG. 4, light measurement subsystem 150 may include a spectrometry device 152 having a light opening 156 that receives light emitted from a portion of a display (e.g., light emitted from sub-region 126 of display 120 shown in FIG. 2A). As used herein, a “spectrometry device” may generally refer to any suitable spectroscopic device capable of measuring light radiation intensity as a function of wavelength. For example, a spectrometry device may be configured to receive and measure light radiation emitted from at least a portion of a light-emitting display. Examples of spectrometry devices may
include, without limitation, spectrometers, spectrophotometers, spectrographs, spectral analyzers, spectroradiometers, spectroscopes, spectral imaging devices, and/or any other suitable spectroscopic device. A spectrometry device may include an optical diffraction grating or prism to separate the incoming light into different light wavelengths and/or light components. The spectrometry device may also include a light detector, which may include multiple light sensors to capture and measure the different light wavelengths and/or light components. Additionally, the spectrometry device may include a collimating portion having, for example, one or more collimating lenses, that collimate incoming light prior to separating the incoming light into various wavelengths and/or light components. The spectrometry device may generate spectrum light information based on the measured light wavelengths and/or light components. The spectrometry device may also receive light from a single region of a display and/or may include scanning functionality to receive light from multiple regions of a display.

[0047] Additionally, as shown in FIG. 4, light measurement subsystem 150 may include at least one camera device that captures light emitted by a light-emitting display. As used herein, a “camera device” may generally refer to any suitable camera or imaging device capable of capturing light emitted by a plurality of regions of a display. Examples of a camera device may include, without limitation, digital cameras that convert captured light into digital signals, such as cameras having charge-coupled device (CCD) image sensors, cameras having complementary metal-oxide semiconductor (CMOS) image sensors, and/or any other suitable camera device. A camera device may include a two-dimensional image sensor array, a lens or lens array to focus light on an image sensor array, and a diaphragm that defines an aperture allowing incoming light to enter the camera and impinge on the image sensor array. The image sensor array may include
a plurality of pixel sensors (e.g., light-sensing photodiode elements) that capture and measure light emitted from various portions of the display. In some examples, the camera device may also include a microlens array to further focus light on the pixel sensors. The camera device may generate location-specific image light information based on the intensity of the captured light emitted by the various portions of the display. In some embodiments, a camera device may include one or more wavelength filters to filter out various light wavelengths and/or light components, allowing only light within a certain range or ranges of wavelengths to reach the image sensor array. For example, the camera device may include a lens filter disposed on or in a lens or lens array and/or a filter or plurality of filters disposed on the image sensor array.

[0048] In some embodiments, light measurement subsystem 150 may include a single camera device that both captures light components having a variety of wavelengths and generates corresponding light information. For example, light measurement subsystem 150 may include a single camera (e.g., camera device 154A) having a color filter array (CFA) or a color filter mosaic (CFM) disposed over an image sensor array. Examples of suitable color filter arrays or mosaics include, without limitation, a red, green, blue (RGB) matrix, a red, green, blue, white (RGBW) matrix, a cyan, yellow, green, magenta (CYGM) matrix, a cyan, magenta, yellow, white (CMYW) matrix, and/or any other suitable color filter matrix. Such a color filter array may capture and quantify light components having various wavelengths and/or ranges of wavelengths from various light-emitting portions of a display.

[0049] In at least one embodiment, light measurement subsystem 150 may include a plurality of camera devices that capture various light components and generate corresponding light information. For example, as shown in FIG. 4, light measurement subsystem 150 may include
a camera device 154A, a camera device 154B, a camera device 154C, and a camera device 154D. Each of camera device 154A, camera device 154B, camera device 154C, and camera device 154D may be configured to capture and measure light components having a separate wavelength or range of wavelengths. For example, out of camera device 154A, camera device 154B, camera device 154C, and camera device 154D, a first camera device may be configured to capture and measure light having a wavelength or range of wavelengths corresponding to red light components, a second camera device may be configured to capture and measure light having a wavelength or range of wavelengths corresponding to blue light components, a third camera device may be configured to capture and measure light having a wavelength or range of wavelengths corresponding to green light components, and a fourth camera device may be configured to capture and measure light of all wavelengths or a specified range of wavelengths (e.g., a range of visible light wavelengths). Camera device 154A, camera device 154B, camera device 154C, and/or camera device 154D may additionally or alternatively be configured to capture light components having any other suitable wavelengths and/or ranges of wavelengths (e.g., cyan light components and/or magenta light components). In some embodiments, light measurement subsystem 150 may include the fewer or greater number of camera devices. Utilizing separate camera devices to capture like components having different wavelengths and/or ranges of wavelengths may enable a greater amount of image light information to be obtained for each of the different wavelengths and/or ranges of wavelengths, enabling greater specificity and accuracy in the calibration of a display and/or enabling the display to be calibrated in a shorter time period.
[0050] Each camera device of light measurement subsystem 150 may include an optical lens or lens array to precisely focus light on the image sensor array of the camera device. For example, as shown in FIG. 4, camera device 154A, camera device 154B, camera device 154C, and camera device 154D may respectively include a camera lens 158A, a camera lens 158B, a camera lens 158C, and a camera lens 158D. In some embodiments, each camera device of light measurement subsystem 150 may also include an optical lens filter, such as a bandpass filter (BPF), that allows passage of light components of a specified wavelength and/or within a specified range of wavelengths. Such optical lens filters may block or inhibit passage of any components outside of the specified wavelength and/or range of wavelengths. For example, as shown in FIG. 4, camera device 154A, camera device 154B, camera device 154C, and camera device 154D may respectively include a lens filter 160A, a lens filter 160B, a lens filter 160C, and a lens filter 160D. According to some examples, lens filter 160A, lens filter 160B, lens filter 160C, and lens filter 160D may include a red color filter, a green color filter, a blue color filter, and/or a clear (e.g., a white) color filter. Additionally or alternatively, lens filter 160A, lens filter 160B, lens filter 160C, and lens filter 160D may include any other suitable color filters, such as, for example, a cyan color filter and/or a magenta color filter. In at least one example, camera device 154A, camera device 154B, camera device 154C, and camera device 154D may capture and measure any light and/or visible light components respectively passing through lens filter 160A, lens filter 160B, lens filter 160C, and lens filter 160D.

[0051] In some embodiments, spectrometry device 152 and each of camera device 154A, camera device 154B, camera device 154C, and camera device 154D may be positioned or oriented to capture light emitted by a display, such as a display mounted to a display mounting
member (e.g., display 120 mounted to a display mounting member 270 illustrated in FIG. 9). For example, as shown in FIG. 4, spectrometry device 152, camera device 154A, camera device 154B, camera device 154C, and camera device 154D may be oriented in the same direction or generally the same direction such that each of spectrometry device 152, camera device 154A, camera device 154B, camera device 154C, and camera device 154D to receive light emitted from a common display. In at least one example, camera device 154A, camera device 154B, camera device 154C, and camera device 154D may be positioned to surround light opening 156 of spectrometry device 152, as shown in FIG. 4. Camera device 154A, camera device 154B, camera device 154C, and/or camera device 154D may additionally or alternatively be disposed in any suitable configuration and/or orientation with respect to light opening 156. According to some examples, spectrometry device 152, camera device 154A, camera device 154B, camera device 154C, and camera device 154D may be configured to simultaneously capture and measure light emitted by a display. Additionally or alternatively, spectrometry device 152, camera device 154A, camera device 154B, camera device 154C, and camera device 154D may be configured to capture light emitted by a display at one or more separate intervals.

[0052] According to at least one embodiment, light measurement subsystem 150 may include a support body 162 for mounting and securing one or more of spectrometry device 152, camera device 154A, camera device 154B, camera device 154C, and camera device 154D. For example, as shown in FIG. 4, support body 162 may include a spectrometry device support member 164 that mounts and secures spectrometry device 152 in a specified position and orientation. Support body 162 may also include a camera device support frame 166 that mounts and secures each of spectrometry device 152, camera device 154A, camera device 154B, camera
device 154C, and camera device 154D in a specified position relative to each other and to spectrometry device 152. In at least one example, support body 162 may allow for positional adjustment of spectrometry device 152, camera device 154A, camera device 154B, camera device 154C, and/or camera device 154D.

[0053] FIG. 5 is a block diagram of an exemplary calibration computing device 180 for calibrating a display, such as display 120 shown in FIG. 2A. Calibration computing device 180 may include a single computing device or a plurality of connected computing devices. As illustrated in FIG. 5, calibration computing device 180 may include one or more modules 181 for performing one or more tasks. As will be explained in greater detail below, calibration computing device 180 may include a communication module 182 that communicates with one or more light measurement devices, such as spectrometry device 152, camera device 154A, camera device 154B, camera device 154C, and/or camera device 154D shown in FIG. 4. In addition, calibration computing device 180 may include a correlation module 183 that correlates light information received from one or more light measurement devices. For example, correlation module 183 may correlate spectrum light information received from spectrometry device 152 with image light information received from one or more of camera device 154A, camera device 154B, camera device 154C, and camera device 154D. Calibration computing device 180 may further include a calibration module 184 that generates calibration data for a display, such as display 120, based on light information received from one or more light measurement devices. For example, calibration module 184 may generate calibration data for display 120 based on spectrum light information received from spectrometry device 152 and image light information received from one or more of camera device 154A, camera device 154B, camera device 154C, and camera
device 154D. Calibration computing device 180 may also include a display driving module 185 that drives and/or provides data for driving a display, such as display 120. For example, display driving module 185 may provide video and/or other image data to, for example, display subsystem 130 shown in FIG. 3 for driving a plurality of pixel elements in a display region of display 120.

[0054] In certain embodiments, one or more of modules 181 in FIG. 5 may represent one or more software applications or programs that, when executed by calibration computing device 180, may cause calibration computing device 180 to perform one or more tasks. As illustrated in FIG. 5, calibration computing device 180 may also include one or more memory devices, such as memory 186. Calibration computing device 180 may also include one or more physical processors, such as physical processor 187. In one example, physical processor 187 may access and/or modify one or more of modules 181 stored in memory 186. Additionally or alternatively, physical processor 187 may execute one or more of modules 181 to facilitate calibration of a display, such as display 120.

[0055] FIG. 6 illustrates an exemplary display calibration system 190 for calibrating a display. As shown in this figure, display calibration system 190 may include a display subsystem 130 (see FIG. 3), a light measurement subsystem 150 (see FIG. 4), and a calibration computing device 180 (see FIG. 5). Spectrometry device 152, camera device 154A, camera device 154B, camera device 154C, and camera device 154D of light measurement subsystem 150 may be positioned and oriented to face display surface 124 of display 120, as illustrated in FIG. 6. Spectrometry device 152 may receive light emitted by a portion of light-emitting region 122 of display 120, such as light emitted from sub-region 126 of light-emitting region 122. Sub-region
may include any suitable portion of light-emitting region 122, such as a region including several sub-pixels (e.g., sub-pixel 128A, sub-pixel 128B, and/or sub-pixel 128C shown in FIG. 2B) up to a region including tens or hundreds of sub-pixels. Spectrometry device 152 may generate spectrum light information based on the received light emitted by a group of sub-pixels in sub-region 126. For example, spectrometry device 152 may collimate and separate light emitted by a group of sub-pixels in sub-region 126 into various light components and may measure the intensity of each light component, and spectrometry device 152 may generate spectrum light information based on the measurements.

[0056] Camera device 154A, camera device 154B, camera device 154C, and camera device 154D may each receive light emitted by at least a portion of light-emitting region 122 that includes sub-region 126 and that is greater than sub-region 126. For example, camera device 154A, camera device 154B, camera device 154C, and/or camera device 154D may receive light emitted by all or substantially all of light-emitting region 122 of display 120. Camera device 154A, camera device 154B, camera device 154C, and/or camera device 154D may generate image light information based on the received light emitted by light-emitting region 122. For example, camera device 154A, camera device 154B, camera device 154C, and/or camera device 154D may filter the light emitted by light-emitting region 122 (e.g., via lens filter 160A, lens filter 160B, lens filter 160C, and/or lens filter 160D) and may focus the light on respective light sensor arrays (e.g., via camera lens 158A, camera lens 158B, camera lens 158C, and/or camera lens 158D) of camera device 154A, camera device 154B, camera device 154C, and/or camera device 154D, which may measure the intensity of certain light components emitted by various regions of light-emitting
region 122. Camera device 154A, camera device 154B, camera device 154C, and/or camera device 154D may generate image light information based on the corresponding measurements.

[0057] In some embodiments, spectrometry device 152, camera device 154A, camera device 154B, camera device 154C, and/or camera device 154D may capture and measure light and/or components of light emitted by light-emitting region 122 in response to instructions sent from communication module 182 of calibration computing device 180. Spectrometry device 152, camera device 154A, camera device 154B, camera device 154C, and/or camera device 154D may then transmit the respective spectrum light information and image light information to calibration computing device 180. In at least one example, display driving module 185 of calibration computing device 180 may drive sub-pixels of display 120 by sending, via communication module 182, instructions and/or image display data to display subsystem 130 such that display 120 emits light from at least a portion of light-emitting region 122 in conjunction with light measurements made by spectrometry device 152, camera device 154A, camera device 154B, camera device 154C, and/or camera device 154D. Communication module 182 of calibration computing device 180 shown in FIG. 5 may receive spectrum light information 192 from spectrometry device 152 and may receive image light information 194 from one or more of camera device 154A, camera device 154B, camera device 154C, and camera device 154D.

[0058] According to at least one embodiment, correlation module 183 of calibration computing device 180 may generate light correlation data 196 based on spectrum light information 192 and image light information 194 received from spectrometry device 152, camera device 154A, camera device 154B, camera device 154C, and/or camera device 154D. Based on the correlation data 196, calibration module 184 may generate display calibration data 198 for
display 120. For example, calibration module 184 may analyze data for sub-pixels (e.g., sub-pixel 128A, sub-pixel 128B, and sub-pixel 128C shown in FIG. 2B) and/or for various groups of sub-pixels of light-emitting region 122 of display 120 based on correlation data 196 and may generate calibration data 198 that includes correction factors to adjust, for example, the light output of one or more sub-pixels and/or groups of sub-pixels of light-emitting region 122. Communication module 182 of calibration computing device 180 may then send the calibration data 198 to display subsystem 130, which utilizes calibration data 198 to drive display 120. In some embodiments, calibration computing device 180 may repeat the calibration process one or more additional times as needed to further calibrate display 120. Accordingly, display calibration system 190 may facilitate real-time calibration of display 120 and may allow for various calibration factors, such as correction factors, to be generated and stored on display subsystem 130 for driving display 120.

[0059] FIG. 7 is a flow diagram of an exemplary computer-implemented method 700 for calibrating a display. The steps shown in FIG. 7 may be performed by any suitable computer-executable code and/or computing system, including display subsystem 130 in FIG. 3, light measurement subsystem 150 in FIG. 4, calibration computing device 180 in FIG. 5, display calibration system 190 in FIG. 6, and/or variations or combinations of one or more of the same. In one example, each of the steps shown in FIG. 7 may represent an algorithm whose structure includes and/or is represented by multiple sub-steps, examples of which will be provided in greater detail below.

[0060] As illustrated in FIG. 7, at step 702 one or more of the systems and/or apparatuses described herein may drive a plurality of sub-pixels in a light-emitting region of a
display. For example, display driving module 185 may, as part of calibration computing device 180, drive a plurality of sub-pixels 128A, 128B, and/or 128C in light-emitting region 122 of display 120 (see, e.g., FIGS. 2A, 2B, 5, and 6).

**[0061]** Display driving module 185 may drive the plurality of sub-pixels 128A, 128B, and/or 128C in light-emitting region 122 of display 120 in a variety of contexts. For example, display driving module 185 may send video data and/or other image data to display subsystem 130 via communication module 182. In response, display subsystem 130 may drive, via display computing device 131, the plurality of sub-pixels 128A, 128B, and/or 128C by selectively applying power and/or driving signals to a TFT array of display 120. In some embodiments, video data and/or other image data supplied by display driving module 185 may specify an illumination intensity for each of the sub-pixels and/or for groups of sub-pixels of display 120.

**[0062]** In some embodiments, two or more sub-pixels of the plurality of sub-pixels may be driven to emit light having different intensities. For example, display driving module 185 may drive the plurality of sub-pixels 128A, 128B, and/or 128C in light-emitting region 122 of display 120 to emit light having different intensities. In at least one embodiment, for example, the plurality of sub-pixels 128A, 128B, and/or 128C may be illuminated in any suitable pattern and/or layout of varying intensities. For example, the plurality of sub-pixels 128A, 128B, and/or 128C may be driven to illuminate the plurality of sub-pixels 128A, 128B, and/or 128C at varying intensities according to an intensity gradient that decreases or increases in intensity over at least a portion of light-emitting region 122. In some examples, the plurality of sub-pixels 128A, 128B, and/or 128C may be driven to illuminate the plurality of sub-pixels 128A, 128B, and/or 128C to produce a desired combination and/or pattern of colors. According to at least one embodiment,
various sub-pixels emitting certain colors and/or at certain locations in light-emitting region 122 may be illuminated during specified time periods and/or at specified intervals, while other sub-pixels emitting other colors may not be illuminated during these specified time periods and/or intervals.

[0063] At step 704 in FIG. 7, one or more of the systems and/or apparatuses described herein may receive, from a spectrometry device, spectrum light information obtained from light emitted by a group of sub-pixels of the plurality of sub-pixels in a sub-region of the display that is both located within the light-emitting region of the display and is smaller than the light-emitting region. For example, communication module 182 of calibration computing device 180 may, as part of calibration computing device 180, receive, from spectrometry device 152, spectrum light information 192 obtained from light emitted by a group of sub-pixels of plurality of sub-pixels 128A, 128B, and/or 128C in a sub-region 126 of display 120 that is located within the light-emitting region 122 of display 120 and that is smaller than the light-emitting region 122 (see, e.g., FIGS. 2A, 2B, and 4-6).

[0064] Communication module 182 may receive spectrum light information 192 from spectrometry device 152 in a variety of contexts. For example, spectrometry device 152 may capture light emitted by the group of sub-pixels 128A, 128B, and/or 128C in sub-region 126 in response to display driving module 185 driving display 120. In at least one example, spectrometry device 152 may collimate the light and separate the light (via, e.g., a diffraction grating) into various individual light components having different wavelengths and/or ranges of wavelengths. Spectrometry device 152 may measure the intensity of each of the components of the received
light to obtain spectrum light information 192, which may then be sent by spectrometry device 152 to calibration computing device 180.

[0065] At step 706 in FIG. 7, one or more of the systems and/or apparatuses described herein may receive, from at least one camera device, image light information obtained from light emitted by the plurality of sub-pixels in the light-emitting region of the display. For example, communication module 182 of calibration computing device 180 may, as part of calibration computing device 180, receive, from camera devices 154A, 154B, 154C, and/or 154D, image light information 194 obtained from light emitted by the plurality of sub-pixels 128A, 128B, and/or 128C in light-emitting region 122 of display 120 (see, e.g., FIGS. 2A, 2B, and 4-6).

[0066] Communication module 182 may receive light information 194 from the camera device(s) in a variety of contexts. For example, camera devices 154A, 154B, 154C, and/or 154D may capture light emitted by the plurality of sub-pixels 128A, 128B, and/or 128C in the entire light-emitting region 122 and/or a portion of display 120 covering a greater region of light-emitting region 122 than sub-region 126. In some examples, each of camera devices 154A, 154B, 154C, and/or 154D may capture and measure components having different wavelengths and/or ranges of wavelengths. For example, camera devices 154A, 154B, 154C, and 154D may each respectively include lens filters 160A, 160B, 160C, and 160D, which may include a red color lens filter, a green color lens filter, a blue color lens filter, and/or a clear lens filter, which removes little or no visible light components.

[0067] In at least one embodiment, communication module 182 may receive, from a plurality of camera devices, a plurality of sets of image light information obtained from the light emitted by the plurality of sub-pixels in the light-emitting region of the display. For example,
communication module 182 may receive a plurality of set of image light information from two or more of camera devices 154A, 154B, 154C, and/or 154D. Each set of light information may correspond to different color light components captured and measured by camera devices 154A, 154B, 154C, and/or 154D. The different sets of light information may be stored as image light information 194 on computing device 180.

[0068] At step 708 in FIG. 7, one or more of the systems and/or apparatuses described herein may generate calibration data for driving the plurality of sub-pixels in the light-emitting region of the display based on the spectrum light information and the image light information. For example, calibration module 184 may, as part of calibration computing device 180, generate display calibration data 198 for driving the plurality of sub-pixels 128A, 128B, and/or 128C in light-emitting region 122 of display 120 based on spectrum light information 192 and image light information 194 (see, e.g., FIGS. 2A, 2B, 5, and 6). Calibration module 184 may generate display calibration data 198 in a variety of contexts. For example, calibration module 184 may generate display calibration data 198 to adjust for inconsistencies in intensities and/or colors of one or more of sub-pixels 128A, 128B, and/or 128C and/or groups of sub-pixels 128A, 128B, and/or 128C.

[0069] According to at least one embodiment, generating the calibration data for driving the plurality of sub-pixels may include correlating the image light information received from the camera device(s) with at least a portion of the spectrum light information received from the spectrometry device. For example, correlation module 183 may, as part of calibration computing device 180, correlate image light information 194 received from camera devices 154A,
154B, 154C, and/or 154D with at least a portion of spectrum light information 192 received from spectrometry device 152 (see, e.g., FIGS. 4-6).

[0070] Correlation module 183 may correlate image light information 194 with at least a portion of spectrum light information 192 in a variety of ways. For example, spectrum light information 192 obtained by spectrometry device 152 may include detailed information on the amounts of various light components having different wavelengths within the light emitted from sub-region 126 of light-emitting region 122 of display 120. This spectrum light information may be correlated to less-detailed image light information 194 obtained from camera devices 154A, 154B, 154C, and/or 154D. For example, each of camera devices 154A, 154B, 154C, and/or 154D may capture image light from all or substantially all of light-emitting region 122, but image light information 194 generated from such captured light may not be as detailed as spectrum light information 192 obtained by spectrometry device 152. However, image light information 194 received from camera devices 154A, 154B, 154C, and/or 154D may include sets of image light information corresponding to different wavelengths and/or ranges of wavelengths of light.

[0071] Correlating portions of spectrum light information 192 obtained by spectrometry device 152 corresponding to various wavelengths and/or ranges of wavelengths with related portions of image light information 194 from camera devices 154A, 154B, 154C, and/or 154D may enable a greater amount of light information to be determined for portions of light-emitting region 122 outside of sub-region 126 based on sets of image light information received from camera devices 154A, 154B, 154C, and/or 154D. In some embodiments, for example, spectrum light information 192 obtained from sub-region 126 may be correlated to portions of image light information 194 corresponding to sub-region 126, and such correlations
may be extrapolated out to portions of image light information 194 corresponding to portions of light-emitting region 122 outside of sub-region 126, enabling more detailed information to be determined based on image light information 194.

[0072] In some examples, calibration module 184 may generate at least one correction factor for driving at least one sub-pixel of the plurality of sub-pixels in the light-emitting region of the display. For example, calibration data 198 may include one or more correction factors to adjust intensities of various individual sub-pixels 128A, 128B, and/or 128C and/or groups of sub-pixels 128A, 128B, and/128C. In some embodiments, the correction factors may be applied to all or substantially all sub-pixels 128A, 128B, and/or 128C in light-emitting region 122 to correct display-wide color inconsistencies and/or nonuniformities. In some embodiments, calibration data 198 may be generated so as to adjust the manner in which light colors emitted by light-emitting region 122 may be perceived by a user. For example, calibration data 198 may be generated so as to adjust the intensity of various sub-pixels 128A, 128B, and/or 128C such that intensities of colors emitted by the display correspond to a chromaticity scale or standard.

[0073] FIG. 8 illustrates a chromaticity diagram 200 showing a two-dimensional projection of a color space. According to at least one embodiments, the colors generated by a display, such as display 120 shown in FIG. 2A, may be represented by the chromaticity values x and y to approximate the colors as perceived by the human eye. The chromaticity values may be computed by transforming, for example, three color intensities (e.g., intensities of colored light emitted by sub-pixels of a display) represented as three tristimulus values X, Y, and Z. For example, X, Y, and Z may be correspond to red intensity, blue intensity, and green intensity.
emitted by sub-pixels of display 120. In some embodiments, the first two tristimulus values X and Y may be normalized by, for example, computing \( x = X/(X+Y+Z) \) and \( y = Y/(X+Y+Z) \) to obtain normalized \( x \) and \( y \) chromaticity values corresponding to the chromaticity diagram. Color intensities may be transformed into tristimulus values using transformations defined by the International Commission on Illumination (CIE) and/or using any other suitable color transformation calculation for computing tristimulus values.

[0074] Colors generated by a display, such as display 120, may be represented by a point (e.g., a coordinate defined by chromaticity values \( x \) and \( y \)) on chromaticity diagram 200. Bounded region 202 of FIG. 8 represents the chromaticity values of all combinations of colors visible to the human eye (i.e., the total available color space). Chromaticity values of colors that may be matched by combining a set of colors emitted by sub-pixels of display 120 may be represented on chromaticity diagram 200 by exemplary sub-region 204 within bounded region 202 of chromaticity diagram 200. As shown in FIG. 8, sub-region 204 may be a triangular shaped region that is defined by lines joining exemplary chromaticity coordinates 206, 208, and 210 (i.e., \( x \) and \( y \) coordinates) corresponding to colors emitted by sub-pixels of display 120 (e.g., red, green, and blue colors respectively emitted by sub-pixels 128A, 128B, and 128C illustrated in FIG. 2B).

[0075] In some embodiments, calibration module 183 may generate calibration data 198 by calculating correction factors for one or more sub-pixels 128A, 128B, and/or 128C in at least a portion of display 120 to ensure that colors displayed by the sub-pixels are perceived by a user in a desired manner. For example, calibration module 183 may perform calculations to correct the illumination intensity of various sub-pixels to ensure that a user perceives colors emitted by display 120 in a desired manner. Such calculations may be based on a specified
chromaticity standard (e.g., a standard corresponding to chromaticity diagram 200 and/or any other suitable standard) to adjust the manner in which various colors displayed by display 120 may be perceived by the human eye. According to at least one embodiment, calibration module 183 may generate calibration data 198 by calculating correction factors for adjusting one or more sub-pixels 128A, 128B, and/or 128C in accordance with a gamma image correction context.

Returning to FIG. 7, according to at least one embodiment method 700 may further include receiving, from the spectrometry device, additional spectrum light information obtained from additional light emitted by the group of sub-pixels or another group of sub-pixels in the light-emitting region of the display. For example, communication module 182 may receive, from spectrometry device 152, additional spectrum light information obtained from additional light emitted by a group of sub-pixels 128A, 128B, and/or 128C in light-emitting region 122 of display 120. In some embodiments, method 700 may also include receiving, from the camera device(s), additional image light information obtained from additional light emitted by the plurality of sub-pixels in the light-emitting region of the display. For example, communication module 182 may receive, from camera device 154A, 154B, 154C, and/or 154D, additional image light information obtained from additional light emitted by the plurality of sub-pixels 128A, 128B, and/or 128C in light-emitting region 122 of display 120. In this example, the additional light emitted by the plurality of sub-pixels 128A, 128B, and/or 128C may be light emitted in accordance with display calibration data 198 generated by calibration module 184.

In at least one embodiment, method 700 may also include determining, based on the additional spectrum light information and/or the additional image light information, whether the display is calibrated to a specified degree when the plurality of sub-pixels in the
light-emitting region of the display are driven utilizing the calibration data. For example, calibration module 184 may, as part of calibration computing device 180, determine whether display 120 is calibrated to a specified degree when the plurality of sub-pixels 128A, 128B, and/or 128 in light-emitting region 122 of display 120 are driven utilizing calibration data 198. In some examples, calibration module 184 may determine, based at least in part on additional spectrum light information received from spectrometry device 152 and/or additional image light information received from camera devices 154A, 154B, 154C, and/or 154D, whether display 120 is calibrated to a specified degree.

[0078] According to some embodiments, method 700 may further include generating modified calibration data for driving the plurality of sub-pixels in the light-emitting region of the display based on the additional spectrum light information and/or the additional image light information. For example, calibration module 184 may, as part of calibration computing device 180, generate modified calibration data for driving the plurality of sub-pixels 128A, 128B, and/or 128 in light-emitting region 122 of display 120 based on additional spectrum light information received from spectrometry device 152 and/or additional image light information received from camera devices 154A, 154B, 154C, and/or 154D. In some examples, the calibration state of display 120 may be evaluated and calibration data for display 120 may be further modified any suitable number of times until display 120 is determined to be calibrated to a desired degree.

[0079] FIG. 9 illustrates an exemplary light measurement subsystem 350 for calibrating a display, such as display 120. As shown in this figure, light measurement subsystem 150 may include camera devices 354A, 354B, 354C, and 354D that each capture light emitted by display 120. Each of camera devices 354A, 354B, 354C, and 354D may be configured to capture
and measure light components having a separate wavelength or range of wavelengths. Additionally, camera devices 354A, 354B, 354C, and 354D may respectively include camera lenses 358A, 358B, 358C, and 358D. Camera devices 354A, 354B, 354C, and 354D may also respectively include lens filters 360A, 360B, 360C, and 360D, which may include a red color filter, a green color filter, a blue color filter, and/or a clear (e.g., a white) color filter. In some embodiments, camera devices 354A, 354B, 354C, and 354D of light measurement subsystem 350 may be utilized in conjunction with a spectrometry device (see, e.g., spectrometry device 152 illustrated in FIGS. 4 and 6) according to any of the systems and methods disclosed herein.

[0080] In some embodiments, light measurement subsystem 350 may include a support body 362 having a support frame 166 that mounts and secures one or more of camera devices 354A, 354B, 354C, and 354D in a desired position and orientation. According to at least one embodiment, camera devices 354A, 354B, 354C, and 354D may be positioned and oriented to capture light emitted by display 120 of display subsystem 130, which may be mounted to a display mounting portion 274 of a display mounting member 270, as illustrated in FIG. 9.

[0081] As discussed throughout the instant disclosure, the disclosed apparatuses, systems, and methods may provide one or more advantages over traditional display calibration apparatuses, systems, and methods. For example, the disclosed display calibration apparatuses, systems, and methods may utilize a spectrometry device in conjunction with at least one camera device, such as, for example, a plurality of color-specific cameras that each capture separate color components of light. Spectrum light information obtained by the spectrometry device may be correlated with image light information obtained by the camera device(s) to more accurately analyze the light emitted by the pixels of the display for purposes of calibrating the pixels. For
example, the detailed spectrum light information obtained by the spectrometer from the portion of the display in the sub-region may be used to interpret the light information obtained by the camera device(s) from the entire light-emitting region of the display, a small portion of which includes the sub-region. By correlating the spectrum light information from the sub-region of the display with the image light information obtained by the camera device(s), an accurate picture of the colors emitted by the entire display may be obtained without the expense and excess time required to obtain spectrometry information for the entire light-emitting region of the display using a spectrometry device. Additionally, because the spectrum light information may be obtained from the sub-region concurrent with obtaining the image light information for the entire display, data may be analyzed and calibration of the display may be performed in real-time.

[0082] Although illustrated as separate elements, the modules described and/or illustrated herein may represent portions of a single module or application. In addition, in certain embodiments one or more of these modules may represent one or more software applications or programs that, when executed by a computing device, may cause the computing device to perform one or more tasks. For example, one or more of the modules described and/or illustrated herein may represent modules stored and configured to run on one or more of the computing devices or systems described and/or illustrated herein. One or more of these modules may also represent all or portions of one or more special-purpose computers configured to perform one or more tasks.

[0083] The process parameters and sequence of the steps described and/or illustrated herein are given by way of example only and can be varied as desired. For example,
while the steps illustrated and/or described herein may be shown or discussed in a particular order, these steps do not necessarily need to be performed in the order illustrated or discussed. The various exemplary methods described and/or illustrated herein may also omit one or more of the steps described or illustrated herein or include additional steps in addition to those disclosed.

[0084] The preceding description has been provided to enable others skilled in the art to best utilize various aspects of the exemplary embodiments disclosed herein. This exemplary description is not intended to be exhaustive or to be limited to any precise form disclosed. Many modifications and variations are possible without departing from the spirit and scope of the instant disclosure. The embodiments disclosed herein should be considered in all respects illustrative and not restrictive. Reference should be made to the appended claims and their equivalents in determining the scope of the instant disclosure.

[0085] Unless otherwise noted, the terms “connected to” and “coupled to” (and their derivatives), as used in the specification and claims, are to be construed as permitting both direct and indirect (i.e., via other elements or components) connection. In addition, the terms “a” or “an,” as used in the specification and claims, are to be construed as meaning “at least one of.” Finally, for ease of use, the terms “including” and “having” (and their derivatives), as used in the specification and claims, are interchangeable with and have the same meaning as the word “comprising.”
ABSTRACT

A display calibration system may include (i) a spectrometry device positioned to capture light emitted by a group of sub-pixels in a sub-region of a display that is both (a) located within a light-emitting region of the display and (b) is smaller than the light-emitting region, (ii) at least one camera device positioned to capture light emitted by a plurality of sub-pixels, in the light-emitting region of the display, that includes the group of sub-pixels, and (iii) a calibration computing device that is (a) communicatively coupled to both the spectrometry device and the at least one camera device and that (b) generates calibration data for driving the plurality of sub-pixels in the light-emitting region of the display based on information received from the spectrometry device and the at least one camera device. Corresponding calibration apparatuses and methods are also disclosed.
FIG. 5

Calibration Computing Device

Memory 186
Modules 181
Communication Module 182
Correlation Module 183
Calibration Module 184
Display Driving Module 185

Physical Processor 187
FIG. 6
Method 700

Start

Drive a plurality of sub-pixels in a light-emitting region of a display 702

Receive, from a spectrometry device, spectrum light information obtained from light emitted by a group of sub-pixels of the plurality of sub-pixels in a sub-region of the display that is located within the light-emitting region of the display and that is smaller than the light-emitting region 704

Receive, from at least one camera device, image light information obtained from light emitted by the plurality of sub-pixels in the light-emitting region of the display 706

Generate calibration data for driving the plurality of sub-pixels in the light-emitting region of the display based on the spectrum light information and the image light information 708

End

FIG. 7
FIG. 8