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## ADAPTIVE STRUCTURED ILLUMINATION FOR OCULAR IMAGING

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### Abstract

Some aspects relate to techniques for imaging a fundus of a subject's eye using an apparatus comprising a digital micromirror device (DMD), a pupil imaging device, and a fundus imaging device. In some embodiments, the techniques include: projecting an illumination pattern onto the subject's eye using the DMD; after projecting the illumination pattern onto the subject's eye, capturing an image of a pupil of the subject's eye using the pupil imaging device; determining, based on the image of the pupil, whether the illumination pattern was projected onto a portion of the subject's eye that is excluded from a target portion of the subject's eye; and after determining that the illumination pattern was not projected onto the portion of the subject's eye that is excluded from the target portion of the subject's eye, capturing an image of the fundus of the subject's eye using the fundus imaging device.

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## **Background/Summary**

CROSS-REFERENCE TO RELATED APPLICATIONS [0001] This application claims the benefit of priority under 35 U.S.C. § 119(e) of U.S. Provisional Patent Application 63/552,726, titled "ADAPTIVE STRUCTURED ILLUMINATION FOR OCULAR IMAGING," filed Feb. 13, 2024, which is incorporated by reference herein in its entirety.

### **BACKGROUND**

[0002] Techniques for imaging and/or measuring a subject's eye would benefit from improvement.

### **SUMMARY**

[0003] Some aspects of the present disclosure relate to techniques for imaging a fundus of a subject's eye using an apparatus comprising a digital micromirror device (DMD), a pupil imaging device, and a fundus imaging device. The techniques include projecting an illumination pattern onto the subject's eye using the DMD; after projecting the illumination pattern onto the subject's eye, capturing an image of a pupil of the subject's eye using the pupil imaging device; determining, based on the image of the pupil, whether the illumination pattern was projected onto a portion of the subject's eye that is excluded from a target portion of the subject's eye; and after determining that the illumination pattern was not projected onto the portion of the subject's eye that is excluded from the target portion of the subject's eye, capturing an image of the fundus of the subject's eye using the fundus imaging device.

[0004] Some aspects of the present disclosure relate to a digital micromirror device (DMD) configured to project illumination patterns onto a subject's eye; a pupil imaging device configured to capture images of a pupil of the subject's eye; a fundus imaging device configured to capture images of a fundus of the subject's eye; and a processor configured to: determine, based on an image of the pupil captured by the pupil imaging device, whether an illumination pattern was projected onto a portion of the subject's eye that is excluded from a target portion of the subject's eye; and after determining that the illumination pattern was not projected onto the portion of the subject's eye that is excluded from the target portion of the subject's eye, transmit instructions to the fundus imaging device configured to cause the fundus imaging device to capture an image of the fundus.

[0005] The foregoing summary is not intended to be limiting. Moreover, various aspects of the present disclosure may be implemented alone or in combination with other aspects.

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## **Description**

### **BRIEF DESCRIPTION OF DRAWINGS**

[0006] Various aspects and embodiments of the disclosure provided herein are described below with reference to the following figures. The accompanying drawings are not intended to be drawn to scale. In the drawings, each identical or nearly identical component that is illustrated in various figures is represented by a like numeral. For purposes of clarity, not every component may be labeled in every drawing. In the drawings:

[0007] FIG. 1A is a schematic view of an example fundus imaging system, according to a first embodiment.

[0008] FIG. 1B is a schematic view of an example fundus imaging system, according to a second embodiment.

[0009] FIG. 2 is a flowchart of an illustrative process for imaging a fundus using an apparatus that includes a digital micromirror device (DMD) component, according to some embodiments.  
[0010] FIG. 3 shows an example of a target imaging portion, according to some embodiments.  
[0011] FIG. 4 shows example illumination patterns, according to some embodiments.  
[0012] FIG. 5 shows an example of a sequence of images used to obtain a combined image, according to some embodiments.  
[0013] FIG. 6 shows an example of a sequence of images used to obtain a combined image, according to some embodiments.  
[0014] FIG. 7 shows an example of a sequence of images used to obtain a combined image, according to some embodiments.  
[0015] FIG. 8 is a schematic diagram of an illustrative computing device with which aspects described herein may be implemented.

#### DETAILED DESCRIPTION

[0016] Aspects of the present disclosure provide improved techniques to assist in imaging a target (e.g., an eye) that are suitable for use in an imaging apparatus operated by a user (e.g., the subject, a clinician, a technician, a doctor, etc.). In some embodiments, the imaging apparatus includes one or more imaging devices including at least a first imaging device (e.g., a pupil imaging device) and a second imaging device (e.g., a fundus imaging device). In some embodiments, the imaging apparatus further includes a digital micromirror device (DMD).

[0017] In some embodiments, the techniques include capturing an image of a subject's pupil after projecting a first illumination pattern onto the eye using a DMD. For example, the DMD may project the first illumination pattern onto the eye using an infrared (IR) illumination source. In some embodiments, the image of the pupil is used to determine whether the first illumination pattern was projected onto a non-target portion of the subject's eye. For example, a target portion may include the pupil, and the non-target portion may include any portion of the eye that does not include the pupil (e.g., the cornea). In some embodiments, after determining that the first illumination pattern was not projected onto a non-target portion, the techniques include capturing an image of the subject's fundus. For example, the image of the fundus may be captured after projecting a second illumination pattern onto the subject's eye.

[0018] Devices for fundus imaging require precise positioning of the eye and the device with respect to one another. For example, the pupil should be positioned with respect to the imaging device such that it is substantially centered and correctly spaced along the planned beam path of the imaging device. When properly aligned, light is transmitted along a beam path through the pupil, where it is projected onto the fundus. When improperly aligned, portions of the eye other than the pupil (e.g., the cornea) are illuminated. Illumination outside of the pupil is not useful. Rather, it causes unnecessary exposure and stray reflections, resulting artifacts that decrease image quality and make the image unsuitable for clinical use.

[0019] However, even when properly aligned, conventional illumination techniques are limited by the size of the pupil, which generally varies between patients. In particular, conventional illumination techniques, such as ring illumination and crescent shape side illumination, are limited by how the paths for illumination and imaging are separated on the pupil and the cornea. Due to these limitations, conventional illumination techniques cannot be implemented in patients with pupils having a diameter smaller than around three millimeters.

[0020] Techniques have been suggested for reducing the negative effects of imaging small pupils using the conventional illumination techniques. For example, polarization, anti-reflective coatings, and light baffling methods have been used to reduce stray light and reflections off of the cornea and optical elements. However, all of these methods are fixed and prove to be useful only in the special cases for which they are optimized.

[0021] Accordingly, the inventors have developed techniques that address the above-described challenges associated with the conventional techniques. In some embodiments, the techniques

include imaging the fundus using an imaging apparatus that includes a digital micromirror device (DMD), a pupil imaging device, and a fundus imaging device. By using a DMD, optimized illumination patterns can be dynamically adapted for each patient, where any misalignment or ocular movements can also be compensated for in real time. For example, in some embodiments, the techniques include projecting a first illumination pattern onto the subject's eye using the DMD, and capturing an image of the pupil after the first illumination pattern is projected onto the subject's eye. To avoid causing the pupil to constrict prior to fundus imaging, the first illumination pattern may be projected using an IR illumination source. In some embodiments, the image of the pupil may be used to determine whether the first illumination pattern was projected onto non-target (e.g., non-pupil) portions of the subject's eye. If the first illumination pattern was projected onto non-target portions of the eye, the DMD may be used to tailor subsequent illumination patterns to avoid projection onto the non-target portions. If the first illumination pattern was not projected onto non-target portions of the eye, an image of the fundus may be captured. For example, the image of the fundus may be captured after a second illumination pattern is projected onto the eye using the DMD and a white light illumination source. The second illumination pattern may be constrained by the boundaries of the first illumination pattern to avoid projecting light onto non-target portions of the eye during fundus imaging.

[0022] Following below are descriptions of various concepts related to, and embodiments of, techniques for imaging the fundus using an apparatus comprising a digital micromirror device (DMD). It should be appreciated that various aspects described herein may be implemented in any of numerous ways, as the techniques are not limited to any particular manner of implementation. Examples of details of implementations are provided herein solely for illustrative purposes. Furthermore, the techniques disclosed herein may be used individually or in any suitable combination, as aspects of the technology described herein are not limited to the use of any particular technique or combination of techniques.

#### Exemplary Apparatus for Fundus Imaging

[0023] FIG. 1A is a schematic view of an example fundus imaging system, according to a first embodiment. As shown, system **100** includes pupil imaging device **130**, fundus imaging device **140**, a digital micromirror device (DMD) **110**, illumination source(s) **120**, and objective lens **122**. In some embodiments, the system **100** additionally, or alternatively, includes beam splitter **124**, lens **126**, and lens **128**. It should be appreciated that system **100** include one or more additional, or alternative, components which are not illustrated in FIG. 1A. For example, system **100** may include computing device(s), actuator(s), additional lens(es), and/or additional beam splitter(s). In some embodiments, one or more (e.g., all) of the components of system **100** may be included in an imaging apparatus.

[0024] In some embodiments, the imaging system **100** may be configured to support an optical path between the DMD **110** and the subject's eye **102**. In the example shown in FIG. 1A, the DMD **110** is configured to use illumination source(s) **120** to project illumination pattern(s) onto the retina plane **104**. In particular, light is directed through lens **126**, reflects off of beam splitter **124**, and is transmitted through the objective lens **122**, after which the illumination pattern is projected onto the retina plane **104**. In the example of FIG. 1A, the pupil and apparatus are aligned, and the illumination pattern has been tailored to the pupil, such that the illumination pattern is projected through the pupil **106** only (as opposed to being projected onto the cornea, or other non-target portions of the eye) and onto the retina plane **104**.

[0025] As described herein, a DMD is an array of individually switchable mirrors that can be used as a rapid spatial light modulator. DMD **110** may include any suitable number of DMDs, each of which may be of any suitable size and include any suitable number of mirrors, as aspects of the technology described herein are not limited in this respect. In some embodiments, DMD **110** may be integrated into a digital light processing (DLP) projector.

[0026] In some embodiments, DMD **110** may be used in conjunction with illumination source(s)

**120.** Illumination source(s) **120** may include any suitable source components such as, for example, light emitting diodes (LED), infrared (IR) light sources, lasers, transparent glass tubes filled with an inert gas (e.g., xenon gas or other noble gas), a quartz tube filled with an inert gas, and/or any other suitable components that are configured to generate illumination light, as aspects of the technology described herein are not limited in this respect. For example, the illumination source(s) **120** may include (a) one or more IR illuminators and/or (b) a white light source (e.g., one or more LEDs).

[0027] In some embodiments, the imaging system **100** may further be configured to support an optical path between the fundus imaging device **140** and the subject's eye **102**. In the example shown in FIG. **1A**, fundus imaging device **140** is configured receive light that has been reflected off of the subject's eye **102** and has been transmitted through both the objective lens **122** and beam splitter **124**. In some embodiments, the fundus imaging device **140** is configured to capture an image of the fundus using the received light.

[0028] In some embodiments, the fundus imaging device **140** may include one or a plurality of image sensors. Such an image sensor may include any suitable image sensor configured to use the received light to generate an image, as aspects of the technology described herein are not limited in this respect. In some embodiments, the image sensor includes a sensing element such as, for example, a two-dimensional array of pixels. The sensing element may be monochrome or color. The sensing element may be a complementary metal-oxide-semiconductor (CMOS) chip, charge-coupled device (CCD) chip, or any other suitable sensing element, as aspects of the technology described herein are not limited in this respect.

[0029] In some embodiments, the imaging system **100** may further be configured to support an optical path between the pupil imaging device **130** and the subject's eye. In some embodiments, the pupil imaging device **130** is configured to capture an image of the pupil using light reflected from the subject's eye.

[0030] In some embodiments, the pupil imaging device **130** may include one or a plurality of image sensors. Such an image sensor may include any suitable image sensor configured to use the received light to generate an image, as aspects of the technology described herein are not limited in this respect. In some embodiments, the image sensor includes a sensing element such as, for example, a two-dimensional array of pixels. The sensing element may be monochrome or color. The sensing element may be a complementary metal-oxide-semiconductor (CMOS) chip, charge-coupled device (CCD) chip, or any other suitable sensing element, as aspects of the technology described herein are not limited in this respect.

[0031] In some embodiments, the pupil imaging device **130** includes multiple stereo image sensors that can be configured to generate and/or output analog and/or digital data representative of a stereo image. In some embodiments, the stereo images. As described herein including at least with respect to FIG. **2**, such a stereo image may be used to align an imaging path of system **100** with the pupil. Though not shown, system **100** may include one or more actuator(s) configured to assist in the alignment by automatically adjusting the position of one or more components of system **100**.

[0032] As shown in FIG. **1A**, the optical path between the pupil imaging device **130** and the subject's eye **102** is distinct from the optical path between the fundus imaging device **140** and the subject's eye **102**. However, in alternative embodiments it can be in the same optical path of the fundus imaging device **140**.

[0033] In some embodiments, imaging system **100** additionally includes one or more computing device(s) (not shown). For example, the computing device(s) may be used to control components of the imaging system such as, for example, the DMD **110**, the illumination source(s) **120**, the fundus imaging device **140**, and/or the pupil imaging device **130**. Additionally, or alternatively, the computing device(s) may be configured to perform one or more acts of process **200** shown in FIG. **2**.

[0034] FIG. **1B** shows an alternative embodiment of an example imaging system. Imaging system

**150** shown in FIG. **1B** may be the same as imaging system **100** except that imaging system **150** includes pupil imaging device **160**. Pupil imaging device **160** may be the same as pupil imaging device **130** except that pupil imaging device **160** shares at least a portion of an optical path with fundus imaging device **140**. For example, the optical path between the subject's eye **102** and pupil imaging device **160** may include at least the objective lens **122**. Though illustrated together, it should be appreciated that the optical path of the fundus imaging device **140** may diverge from the optical path of the pupil imaging device **160** via one or more optical components (not shown) such as, for example, one or more beam splitters, lenses, mirrors, or any other suitable optical component(s).

[0035] In some embodiments, the pupil imaging device **160** additionally, or alternatively, includes a split image component **165** such as, for example, a split prism or a split mirror. In some embodiments, the split image component **165** is configured to generate a split image, and the split image may be used to align the pupil with the imaging path of imaging system **150**. Techniques for performing such an alignment are described herein including at least with respect to FIG. **2**. As described above, one or more actuator(s) (not shown) of system **150** may be used to assist in the alignment.

#### Exemplary Fundus Imaging Techniques

[0036] FIG. **2** is a flowchart of an illustrative process for imaging a subject's fundus, according to some embodiments. One or more of acts (e.g., all of the acts) of process **200** may be performed automatically by any suitable computing device(s). For example, the act(s) may be performed by a System on Module (SOM) computer, laptop computer, a desktop computer, one or more servers, in a cloud computing environment, computing device **800** described herein with respect to FIG. **8**, and/or in any other suitable way.

[0037] At act **202**, a first illumination pattern is projected onto the eye using a digital micromirror device (DMD) (e.g., the DMD **110** shown in FIGS. **1A** and **1B**). The first illumination pattern may include any suitable illumination pattern, as aspects of the technology are not limited in this respect. Nonlimiting examples of illumination patterns are shown in FIG. **4** (e.g., example pattern **405**, pattern **410**, pattern **415**, pattern **420**, pattern **425**, pattern **430**, pattern **435**, and pattern **440**).

[0038] In some embodiments, the DMD is configured to project an illumination pattern having particular dimensions. The dimensions may be determined using any suitable techniques, as aspects of the technology described herein are not limited in this respect. For example, the dimensions may be determined based on an estimated or measured size of a target portion of the eye (e.g., the pupil). In particular, the dimensions may be determined in an effort to project the illumination pattern onto the target portion of the eye (e.g., the pupil), rather than onto a non-target portion of the eye (e.g., the cornea). FIG. **3** shows an example of a target **350** and non-target **310** portion of the eye.

[0039] When the dimensions of the first illumination pattern are determined based on the size of the pupil, the size of the pupil may be estimated or measured using any suitable techniques, as aspects of the technology described herein are not limited in this respect. For example, the size of the pupil may be estimated based on pupil sizes measured for one or more other subjects (e.g., an average pupil size). Additionally, or alternatively, the size of the pupil of the particular subject may be measured using any suitable pupil measurement techniques, as aspects of the technology described herein are not limited in this respect. For example, the size of the subject's pupil may be measured based on a previously captured image of the subject's pupil. In this case, the size of the pupil may be measured by (a) measuring the size (e.g., the diameter) of the pupil in the image, and (b) multiplying the measured size by a scaling value. In some embodiments, the image is captured using the pupil imaging device described with respect to act **204**.

[0040] In some embodiments, the DMD projects the first illumination pattern onto the eye using an illumination source. To avoid causing the pupil to constrict in size prior to imaging the fundus, the illumination source may include an infrared illumination source. Alternatively, the illumination

source may include any other suitable illumination source such as, for example, a white light illumination source, as aspects of the technology described herein are not limited in this respect. [0041] At act **204**, an image of the pupil is captured using a pupil imaging device. In some embodiments, the image is captured after the first illumination pattern is projected onto the eye. An example of the pupil imaging device is described herein including at least with respect FIG. **1A** and FIG. **1B**.

[0042] At act **206**, it is determined whether to adjust a position of the apparatus (e.g., the apparatus comprising the DMD) and/or a position of the subject based on the image captured at act **206**. In some embodiments, this includes determining whether the fundus imaging device is aligned with the pupil. This may be achieved using any suitable techniques, as aspects of the technology described herein are not limited in this respect. If the fundus imaging device is aligned with the pupil, then no adjustment may be needed. If the fundus imaging device is not aligned with the pupil, then an adjustment may be needed.

[0043] One example technique for determining whether the fundus imaging device is aligned with the pupil includes localizing a pupil in a field of view of the fundus imaging device using a split image of the fundus. For example, as described herein including at least with respect to FIG. **1B**, the pupil imaging device may include a split image component (e.g., a split prism or a split mirror), and the image captured at act **204** may be a split image of the pupil. The split image may be split into image portions (e.g., halves, quarters, etc.). If the portions of the split image are aligned with one another, and the pupil is centered in the image, this may indicate that the fundus imaging device is aligned with the pupil. If the portions of the split image are misaligned, this may indicate that the pupil is positioned too close or too far from the fundus camera. The degree of displacement between the misaligned image portions may be used to determine how to position the subject and/or the fundus imaging device such that they are aligned. If the pupil is not centered in the image, this may indicate that the fundus imaging device and pupil are misaligned along a plane perpendicular to the imaging path. The displacement between the center of the pupil and the center of the image may be used to determine how to position the subject and/or the fundus imaging device such that they are aligned.

[0044] As an additional, or alternative example, determining whether the fundus imaging device is aligned with the pupil may include determining a gaze angle of the subject's eye. In some embodiments, the gaze angle is determined based on a stereo image of the subject's eye. For example, the pupil imaging device may include a stereo camera, and the image captured at act **204** may be a stereo image. Alternatively, the image captured at act **204** may be one of two images used to generate a stereo image. In some embodiments, determining the gaze angle of the subject's eye includes using the stereo image to determine the major and minor axes of the pupil, and determining the gaze angle based on the major and minor axes. If the gaze angle is oriented towards an intended target (e.g., a fixation target), this may indicate that the pupil is aligned with the fundus imaging device. If the gaze angle is not oriented towards the intended target, then this may indicate that the pupil is not aligned with the fundus imaging device, and the measured gaze angle may be used to determine how to position the fundus imaging device such that they are aligned. Example techniques for determining gaze angle are described in U.S. Provisional Patent Application No. 63/588,609, which is incorporated by reference herein in its entirety.

[0045] If, at act **206**, it is determined that a position of the apparatus and/or subject should be adjusted, process **200** proceeds to act **208**. At act **208**, a position of the apparatus and/or subject is adjusted. In some embodiments, adjusting the position of the subject includes outputting instructions to an operator of the apparatus (e.g., the subject or another user) with respect to how the subject should be repositioned. In some embodiments, adjusting the position of the apparatus includes automatically adjusting the position of the apparatus using an actuator configured to adjust the position of the apparatus. Alternatively, adjusting the position of the apparatus includes outputting instructions to an operator of the apparatus (e.g., the subject or another user).

[0046] After the position of the subject and/or apparatus is adjusted at act **208**, process **200** returns to act **202**. For example, acts **202**, **204**, **206**, and **208** may be repeated until it is determined, at act **206**, that the position of the subject and/or apparatus should not be adjusted.

[0047] If, at act **206**, it is determined that the position of the apparatus and/or subject should not be adjusted, process **200** proceeds to act **210**. At act **210**, it is determined whether the first illumination pattern was projected onto a portion of the eye that is excluded from a target portion. In some embodiments, this may include evaluating otherwise processing the image captured at **204** to determine whether the first illumination pattern was projected onto a portion of the eye excluded from the target region. This may include user evaluation of the image. For example, the user may visually inspect the image. If the first illumination pattern was projected onto a non-target portion of the eye, then the image may include reflections and/or other image artifacts. Alternatively, any suitable image processing techniques may be used to determine whether the first illumination pattern was projected onto a non-target portion of the eye. For example, the image may be processed using a machine learning model trained to predict whether the illumination pattern was projected onto non-target portions of the eye and/or identify portions of the eye that have been illuminated.

[0048] If, at act **210**, it is determined that the first illumination pattern was projected onto a portion of the eye excluded from the target portion, process **200** returns to act **202**, during which an illumination pattern different from the first illumination pattern is projected onto the eye using the DMD. In some embodiments, the illumination pattern is generated based on the image that was captured at act **204**. For example, the position of the artifacts and/or reflections in the image may be used, as feedback, to determine how to adjust the illumination pattern (e.g., using the DMD) to avoid again projecting the illumination pattern onto the non-target portions of the eye. Additionally, or alternatively, the image captured at act **204** may be used to determine updated measurements of the pupil (e.g., as described with respect to act **202**), and the illumination pattern may be tailored to the updated measurements.

[0049] After the illumination pattern is generated and projected onto the subject's eye at act **202**, one or more of acts **204**, **206**, **208**, and **210** may be repeated.

[0050] If, at act **210**, it is determined that the first illumination pattern was not projected onto a portion of the eye excluded from the target portion (e.g., the illumination pattern was projected solely onto the subject's pupil), process **200** proceeds to act **212**. At act **212**, a second illumination pattern is projected onto the eye using the DMD. In some embodiments, the second illumination pattern is the same illumination pattern (e.g., same size and shape) as the first illumination pattern. Alternatively, the second illumination pattern may be different from the first illumination pattern. When the second illumination pattern is different from the first illumination pattern, the second illumination pattern may be constrained by the boundaries of the first illumination pattern. For example, the boundaries of the second illumination pattern may be the same as the boundaries of the first illumination pattern or positioned within the boundaries of the first illumination pattern to avoid illuminating non-target portions of the subject's eye.

[0051] In some embodiments, the DMD projects the second illumination pattern onto the eye using an illumination source suitable for capturing a fundus image. For example, the illumination source may be a white light source.

[0052] At act **214**, an image of the fundus is captured using a fundus imaging device. In some embodiments, the image is captured after the second illumination pattern is projected onto the eye. An example of the fundus imaging device is described herein including at least with respect FIG. **1A** and FIG. **1B**.

[0053] At act **216**, it is determined whether another image of the fundus should be captured. For example, in some embodiments, it may be desirable to project different illumination patterns onto the eye and capture a respective sequence of images. For example, with reference to FIG. **4**, one fundus image may be captured after example illumination pattern **415** is projected onto the



subject's eye, and a subsequent image may be captured after example illumination pattern **420** is projected onto the subject's eye. Due to the DMD's ability to rapidly modify the illumination pattern, such a sequence of images may be captured within a very short time of one another before the pupil constricts (e.g., within milliseconds of one another). Any suitable number of images may be captured in the sequence of images within the time constraint imposed by pupil constriction, as aspects of the technology are not limited in this respect.

[0054] Accordingly, if, at act **216**, it is determined that another image should be captured, act **212** and act **214** are repeated to capture another fundus image in the sequence of fundus images. As described above, at act **212**, an illumination pattern different from the second illumination pattern may be projected onto the eye. At act **214**, the respective fundus image may be captured.

[0055] In some embodiments, if a sequence of fundus images is captured during acts **212-216**, said images may be combined to generate one or more combined fundus images. Combining the fundus images may improve the contrast, eliminate artifacts (e.g., reflections), and/or improve one or more other characteristics of the resulting combined fundus image(s). FIG. 5, FIG. 6, and FIG. 7 each show an example of two fundus images that were combined to generate a third, combined image that excludes artifacts depicted in the two individual images. In particular, with respect to FIG. 5, image **510** and image **520** were combined to generate image **530**. With respect to FIG. 6, image **610** and image **620** were combined to generate image **630**. With respect to FIG. 7, image **710** and image **720** were combined to generate image **730**.

[0056] If it is determined that another image should not be captured, process **200** ends.

#### Computer Implementation

[0057] An illustrative implementation of a computer system **800** that may be used in connection with any of the embodiments of the technology described herein (e.g., such as the process of FIG. 2) is shown in FIG. 8. The computer system **800** includes one or more processors **810** and one or more articles of manufacture that comprise non-transitory computer-readable storage media (e.g., memory **820** and one or more non-volatile storage media **830**). The processor **810** may control writing data to and reading data from the memory **820** and the non-volatile storage device **830** in any suitable manner, as the aspects of the technology described herein are not limited to any particular techniques for writing or reading data. To perform any of the functionality described herein, the processor **810** may execute one or more processor-executable instructions stored in one or more non-transitory computer-readable storage media (e.g., the memory **820**), which may serve as non-transitory computer-readable storage media storing processor-executable instructions for execution by the processor **810**.

[0058] Computing device **800** may include a network input/output (I/O) interface **840** via which the computing device may communicate with other computing devices. Such computing devices may be interconnected by one or more networks in any suitable form, including a local area network or a wide area network, such as an enterprise network, an intelligent network (IN) or the Internet. Such networks may be based on any suitable technology and may operate according to any suitable protocol and may include wireless networks, wired networks or fiber optic networks.

[0059] Computing device **800** may also include one or more user I/O interfaces **850**, via which the computing device may provide output to and receive input from a user. The user I/O interfaces may include devices such as a keyboard, a mouse, a microphone, a display device (e.g., a monitor or touch screen), speakers, a camera, and/or various other types of I/O devices.

[0060] Further, it should be appreciated that a computer may be embodied in any of a number of forms, such as a rack-mounted computer, a System on Module (SOM) computer, a desktop computer, a laptop computer, or a tablet computer, as non-limiting examples. Additionally, a computer may be embedded in a device not generally regarded as a computer but with suitable processing capabilities, including a Personal Digital Assistant (PDA), a smartphone, a tablet, or any other suitable portable or fixed electronic device.

[0061] The above-described embodiments can be implemented in any of numerous ways. For

example, the embodiments may be implemented using hardware, software, or a combination thereof. When implemented in software, the software code can be executed on any suitable processor (e.g., a microprocessor) or collection of processors, whether provided in a single computing device or distributed among multiple computing devices. It should be appreciated that any component or collection of components that perform the functions described above can be generically considered as one or more controllers that control the above-described functions. The one or more controllers can be implemented in numerous ways, such as with dedicated hardware, or with general purpose hardware (e.g., one or more processors) that is programmed using microcode or software to perform the functions recited above.

[0062] In this respect, it should be appreciated that one implementation of the embodiments described herein comprises at least one computer-readable storage medium (e.g., RAM, ROM, EEPROM, flash memory or other memory technology, CD-ROM, digital versatile disks (DVD) or other optical disk storage, magnetic cassettes, magnetic tape, magnetic disk storage or other magnetic storage devices, or other tangible, non-transitory computer-readable storage medium) encoded with a computer program (i.e., a plurality of executable instructions) that, when executed on one or more processors, performs the above-described functions of one or more embodiments. The computer-readable medium may be transportable such that the program stored thereon can be loaded onto any computing device to implement aspects of the techniques described herein. In addition, it should be appreciated that the reference to a computer program which, when executed, performs any of the above-described functions, is not limited to an application program running on a host computer. Rather, the terms computer program and software are used herein in a generic sense to reference any type of computer code (e.g., application software, firmware, microcode, or any other form of computer instruction) that can be employed to program one or more processors to implement aspects of the techniques described herein.

[0063] The terms “program” or “software” are used herein in a generic sense to refer to any type of computer code or set of computer-executable instructions that can be employed to program a computer or other processor to implement various aspects as described above. Additionally, it should be appreciated that according to one aspect, one or more computer programs that when executed perform methods of the present disclosure need not reside on a single computer or processor but may be distributed in a modular fashion among a number of different computers or processors to implement various aspects of the present disclosure.

[0064] Computer-executable instructions may be in many forms, such as program modules, executed by one or more computers or other devices. Generally, program modules include routines, programs, objects, components, data structures, etc. that perform particular tasks or implement particular abstract data types. Typically, the functionality of the program modules may be combined or distributed as desired in various embodiments.

[0065] Also, data structures may be stored in computer-readable media in any suitable form. For simplicity of illustration, data structures may be shown to have fields that are related through location in the data structure. Such relationships may likewise be achieved by assigning storage for the fields with locations in a computer-readable medium that convey relationship between the fields. However, any suitable mechanism may be used to establish a relationship between information in fields of a data structure, including through the use of pointers, tags or other mechanisms that establish relationship between data elements.

[0066] When implemented in software, the software code can be executed on any suitable processor or collection of processors, whether provided in a single computer or distributed among multiple computers.

[0067] The foregoing description of implementations provides illustration and description but is not intended to be exhaustive or to limit the implementations to the precise form disclosed.

Modifications and variations are possible in light of the above teachings or may be acquired from practice of the implementations. In other implementations the methods depicted in these figures

may include fewer operations, different operations, differently ordered operations, and/or additional operations. Further, non-dependent blocks may be performed in parallel.

[0068] It will be apparent that example aspects, as described above, may be implemented in many different forms of software, firmware, and hardware in the implementations illustrated in the figures.

## CONCLUSION

[0069] Having thus described several aspects and embodiments of the technology set forth in the disclosure, it is to be appreciated that various alterations, modifications, and improvements will readily occur to those skilled in the art. Such alterations, modifications, and improvements are intended to be within the spirit and scope of the technology described herein. For example, those of ordinary skill in the art will readily envision a variety of other means and/or structures for performing the function and/or obtaining the results and/or one or more of the advantages described herein, and each of such variations and/or modifications is deemed to be within the scope of the embodiments described herein. Those skilled in the art will recognize or be able to ascertain using no more than routine experimentation, many equivalents to the specific embodiments described herein. It is, therefore, to be understood that the foregoing embodiments are presented by way of example only and that, within the scope of the appended claims and equivalents thereto, inventive embodiments may be practiced otherwise than as specifically described. In addition, any combination of two or more features, systems, articles, materials, kits, and/or methods described herein, if such features, systems, articles, materials, kits, and/or methods are not mutually inconsistent, is included within the scope of the present disclosure.

[0070] The acts performed as part of the methods may be ordered in any suitable way. Accordingly, embodiments may be constructed in which acts are performed in an order different than illustrated, which may include performing some acts simultaneously, even though shown as sequential acts in illustrative embodiments.

[0071] All definitions, as defined and used herein, should be understood to control over dictionary definitions, definitions in documents incorporated by reference, and/or ordinary meanings of the defined terms.

[0072] The indefinite articles “a” and “an,” as used herein in the specification and in the claims, unless clearly indicated to the contrary, should be understood to mean “at least one.”

[0073] The phrase “and/or,” as used herein in the specification and in the claims, should be understood to mean “either or both” of the elements so conjoined, i.e., elements that are conjunctively present in some cases and disjunctively present in other cases. Multiple elements listed with “and/or” should be construed in the same fashion, i.e., “one or more” of the elements so conjoined. Other elements may optionally be present other than the elements specifically identified by the “and/or” clause, whether related or unrelated to those elements specifically identified. Thus, as a non-limiting example, a reference to “A and/or B”, when used in conjunction with open-ended language such as “comprising” can refer, in one embodiment, to A only (optionally including elements other than B); in another embodiment, to B only (optionally including elements other than A); in yet another embodiment, to both A and B (optionally including other elements); etc.

[0074] As used herein in the specification and in the claims, the phrase “at least one,” in reference to a list of one or more elements, should be understood to mean at least one element selected from any one or more of the elements in the list of elements, but not necessarily including at least one of each and every element specifically listed within the list of elements and not excluding any combinations of elements in the list of elements. This definition also allows that elements may optionally be present other than the elements specifically identified within the list of elements to which the phrase “at least one” refers, whether related or unrelated to those elements specifically identified. Thus, as a non-limiting example, “at least one of A and B” (or, equivalently, “at least one of A or B,” or, equivalently “at least one of A and/or B”) can refer, in one embodiment, to at least one, optionally including more than one, A, with no B present (and optionally including elements

other than B); in another embodiment, to at least one, optionally including more than one, B, with no A present (and optionally including elements other than A); in yet another embodiment, to at least one, optionally including more than one, A, and at least one, optionally including more than one, B (and optionally including other elements); etc.

[0075] Also, the phraseology and terminology used herein is for the purpose of description and should not be regarded as limiting. The use of “including,” “comprising,” or “having,” “containing,” “involving,” and variations thereof herein, is meant to encompass the items listed thereafter and equivalents thereof as well as additional items.

[0076] In the claims, as well as in the specification above, all transitional phrases such as “comprising,” “including,” “carrying,” “having,” “containing,” “involving,” “holding,” “composed of,” and the like are to be understood to be open-ended, i.e., to mean including but not limited to. Only the transitional phrases “consisting of” and “consisting essentially of” shall be closed or semi-closed transitional phrases, respectively.

## Claims

1. A method for imaging a fundus of a subject's eye using an apparatus comprising a digital micromirror device (DMD), a pupil imaging device, and a fundus imaging device, the method comprising: projecting an illumination pattern onto the subject's eye using the DMD; after projecting the illumination pattern onto the subject's eye, capturing an image of a pupil of the subject's eye using the pupil imaging device; determining, based on the image of the pupil, whether the illumination pattern was projected onto a portion of the subject's eye that is excluded from a target portion of the subject's eye; and after determining that the illumination pattern was not projected onto the portion of the subject's eye that is excluded from the target portion of the subject's eye, capturing an image of the fundus of the subject's eye using the fundus imaging device.
2. The method of claim 1, wherein the target portion of the subject's eye comprises the pupil.
3. The method of claim 1, wherein the image of the pupil is a first image, wherein the illumination pattern is a first illumination pattern, and wherein the method further comprises: after determining that the first illumination pattern was projected onto the portion of the subject's eye that is excluded from the target portion, projecting a second illumination pattern onto the subject's eye, the second illumination pattern being different from the first illumination pattern; after projecting the second illumination pattern onto the subject's eye, capturing a second image of the pupil; and determining, based on the second image, whether the second illumination pattern was projected onto the portion of the subject's eye that is excluded from the target portion.
4. The method of claim 3, further comprising: determining, using the image of the pupil, a size and/or location of the pupil; and generating the second illumination pattern based on the determined size and/or location of the pupil.
5. The method of claim 1, wherein the illumination pattern is a first illumination pattern, and wherein the method further comprises: generating a second illumination pattern based on the first illumination pattern; and projecting the second illumination pattern onto the subject's eye using the DMD, wherein capturing the image of the fundus comprises capturing the image of the fundus after projecting the second illumination pattern onto the subject's eye.
6. The method of claim 5, wherein the first illumination pattern has first boundaries, and wherein the second illumination pattern has second boundaries that are within the first boundaries of the first illumination pattern.
7. The method of claim 5, wherein projecting the first illumination pattern onto the subject's eye comprises projecting the first illumination pattern onto the subject's eye using the DMD and a first illumination source, and wherein projecting the second illumination pattern onto the subject's eye comprises projecting the second illumination pattern onto the subject's eye using the DMD and a

second illumination source.

**8.** The method of claim 7, wherein the first illumination source is an infrared (IR) illumination source, and wherein the second illumination source is a white light illumination source.

**9.** The method of claim 1, further comprising: generating a plurality of illumination patterns based on the illumination pattern; sequentially projecting the plurality of illumination patterns onto the subject's eye; and after projecting each of the plurality of illumination patterns onto the subject's eye, capturing a respective image of the fundus to obtain a plurality of images of the fundus.

**10.** The method of claim 9, further comprising: combining the plurality of images of the fundus to obtain one or more combined images of the fundus.

**11.** The method of claim 10, further comprising: determining, based on the image of the pupil, a size and/or location of the pupil, wherein combining the plurality of images of the fundus to obtain the one or more combined images of the fundus comprises combining the plurality of images of the fundus based on the determined size and/or location of the pupil.

**12.** The method of claim 1, further comprising: adjusting a position of the apparatus and/or a position of the subject based on the image of the pupil.

**13.** The method of claim 12, wherein the pupil imaging device includes a split image component, wherein capturing the image of the pupil comprises capturing a split image of the pupil, and wherein adjusting the position of the apparatus and/or the position of the subject based on the image of the pupil comprises adjusting the position of the apparatus and/or the position of the subject based on a displacement between portions of the split image of the pupil.

**14.** The method of claim 12, wherein adjusting the position of the apparatus and/or the position of the subject based on the image of the pupil comprises: determining whether the pupil is oriented towards an intended fixation target direction based on a gaze angle associated with the pupil in the image of the pupil; and adjusting the position of the apparatus and/or the position of the subject after determining that the pupil is not oriented towards the intended fixation target direction.

**15.** A system, comprising: a digital micromirror device (DMD) configured to project illumination patterns onto a subject's eye; a pupil imaging device configured to capture images of a pupil of the subject's eye; a fundus imaging device configured to capture images of a fundus of the subject's eye; and a processor configured to: determine, based on an image of the pupil captured by the pupil imaging device, whether an illumination pattern was projected onto a portion of the subject's eye that is excluded from a target portion of the subject's eye; and after determining that the illumination pattern was not projected onto the portion of the subject's eye that is excluded from the target portion of the subject's eye, transmit instructions to the fundus imaging device configured to cause the fundus imaging device to capture an image of the fundus.

**16.** The system of claim 15, wherein the illumination pattern is a first illumination pattern, wherein the processor is further configured to transmit instructions to the DMD configured to cause the DMD to project a second illumination pattern onto the subject's eye, and wherein the fundus imaging device is configured to capture the image of the fundus after the DMD projects the second illumination pattern onto the subject's eye.

**17.** The system of claim 16, further comprising: multiple illumination sources including at least a first illumination source and a second illumination source, wherein the DMD is configured to use the first illumination source to project the first illumination pattern onto the subject's eye, and wherein the DMD is configured to use the second illumination source to project the second illumination pattern onto the subject's eye.

**18.** The system of claim 17, wherein the first illumination source is an infrared illumination source, and wherein the second illumination source is a white light illumination source.

**19.** The system of claim 15, wherein the image of the pupil is a first image of the pupil, wherein the illumination pattern is a first illumination pattern, and wherein the processor is further configured to: after determining that the illumination pattern was projected onto the portion of the subject's eye that is excluded from the target portion of the subject's eye: transmit instructions to the DMD

configured to cause the DMD to project a second illumination pattern onto the subject's eye, wherein the second illumination pattern is different from the first illumination pattern; and transmit instructions to the pupil imaging device configured to cause the pupil imaging device to capture a second image of the pupil after the DMD projects the second illumination pattern onto the subject's eye.

**20.** The system of claim 15, further comprising an actuator configured to align an imaging path of the fundus imaging device with the pupil.

**21.** The system of claim 20, wherein the pupil imaging device comprises a split image component, wherein the image of the pupil is a split image, and wherein the processor is further configured to: process the split image to determine whether the imaging path of the fundus imaging device is aligned with the pupil; and after determining that the imaging path of the fundus imaging device is not aligned with the pupil, transmit instructions to the actuator configured to cause the actuator to align the imaging path of the fundus imaging device with the pupil.

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