United States Patent	12383131
Kind Code	B2
Date of Patent	August 12, 2025
Inventor(s)	Raymond; Thomas Daniel et al.

Apparatus and method for automated non-contact eye examination

Abstract

An eye measurement system includes an optical system. The eye measurement system is disposed in a housing which includes an aperture for providing light to and from the optical system and a subject's eye while the subject is separated and spaced apart from the housing, and the eye is not maintained in a fixed positional relationship with respect to the housing. An optical system movement arrangement moves the optical system. An automatic eye tracking arrangement ascertains a current positional relationship of the eye with respect to the optical system without human assistance, and in response thereto controls the optical system movement arrangement to move the optical system into a predetermined positional relationship with respect to the eye, for measurement of the eye, without human assistance. The eye measurement system can make objective, and/or subjective, refraction measurements of the eye.

Inventors: **Raymond; Thomas Daniel** (Edgewood, NM), **Farrer; Stephen W** (Albuquerque, NM)

Applicant: **Raymond; Thomas Daniel** (Edgewood, NM); **Farrer; Stephen W** (Albuquerque, NM)

Family ID: **1000008747639**

Assignee: **Scintellite, LLC (Albuquerque, NM)**

Appl. No.: **18/401475**

Filed: **December 30, 2023**

Prior Publication Data

Document Identifier	Publication Date
US 20240215822 A1	Jul. 04, 2024

Related U.S. Application Data

Publication Classification

Int. Cl.: **A61B3/113** (20060101); **A61B3/00** (20060101); **A61B3/10** (20060101); **A61B3/103** (20060101); **A61B3/12** (20060101); **A61B3/135** (20060101); **A61B3/16** (20060101); **G16H40/67** (20180101)

U.S. Cl.:

CPC   **A61B3/113** (20130101); **A61B3/0008** (20130101); **A61B3/0025** (20130101); **A61B3/0041** (20130101); **A61B3/102** (20130101); **A61B3/103** (20130101); **A61B3/12** (20130101); **A61B3/135** (20130101); **A61B3/16** (20130101); **G16H40/67** (20180101);

Field of Classification Search

CPC: A61B (3/113); A61B (3/0008); A61B (3/0025); A61B (3/0041); A61B (3/102); A61B (3/103); A61B (3/12); A61B (3/135); A61B (3/16); G16H (40/67)

USPC: 351/209

References Cited

U.S. PATENT DOCUMENTS

Patent No.	Issued Date	Patentee Name	U.S. Cl.	CPC
3879113	12/1974	Howland et al.	N/A	N/A
4209252	12/1979	Arditty et al.	N/A	N/A
4834527	12/1988	Kobayashi	N/A	N/A
5094521	12/1991	Jolson et al.	N/A	N/A
5420650	12/1994	Kohayakawa	N/A	N/A
5532769	12/1995	Miwa et al.	N/A	N/A
5708494	12/1997	Iijima et al.	N/A	N/A
6309068	12/2000	Kohayakawa	N/A	N/A
6361167	12/2001	Su et al.	N/A	N/A
6669340	12/2002	Percival et al.	N/A	N/A
7232220	12/2006	Franz et al.	N/A	N/A
7357506	12/2007	Shimizu et al.	N/A	N/A
7367675	12/2007	Maddalena et al.	N/A	N/A
7520611	12/2008	Franz et al.	N/A	N/A
7533991	12/2008	Baumann et al.	N/A	N/A
7588336	12/2008	Honda	N/A	N/A
7631970	12/2008	Wei	N/A	N/A
7708406	12/2009	Koest	N/A	N/A
7818041	12/2009	Kim et al.	N/A	N/A
7840418	12/2009	Shoenberg	N/A	N/A
7909462	12/2010	Takahashi et al.	N/A	N/A
8123353	12/2011	Biernat et al.	N/A	N/A

8444270	12/2012	Nordstrom	N/A	N/A
8793142	12/2013	Fishman et al.	N/A	N/A
9173563	12/2014	Buckland et al.	N/A	N/A
9230062	12/2015	Seriani	N/A	N/A
9277863	12/2015	Liang	N/A	N/A
9301675	12/2015	Kiderman et al.	N/A	N/A
9380934	12/2015	Sugiura et al.	N/A	N/A
9504378	12/2015	Lee et al.	N/A	N/A
9730578	12/2016	Lai	N/A	N/A
9980644	12/2017	Fried et al.	N/A	N/A
10022050	12/2017	Isogai	N/A	N/A
10083279	12/2017	Seriani	N/A	N/A
10264966	12/2018	Yamamoto et al.	N/A	N/A
10524658	12/2019	Fried et al.	N/A	N/A
10583039	12/2019	Raymond et al.	N/A	N/A
10602928	12/2019	Fried et al.	N/A	N/A
10734114	12/2019	Seriani	N/A	N/A
10762994	12/2019	Seriani	N/A	N/A
10827925	12/2019	Fried et al.	N/A	N/A
10874299	12/2019	Seriani	N/A	N/A
11324400	12/2021	Raymond	N/A	G16H 30/40
2003/0117580	12/2002	Franz et al.	N/A	N/A
2006/0026051	12/2005	Rose	N/A	N/A
2006/0084856	12/2005	Biggins et al.	N/A	N/A
2006/0290885	12/2005	Covannon et al.	N/A	N/A
2007/0171367	12/2006	Sebastian et al.	N/A	N/A
2007/0195267	12/2006	Franz et al.	N/A	N/A
2008/0284979	12/2007	Yee et al.	N/A	N/A
2009/0080712	12/2008	D'Souza et al.	N/A	N/A
2009/0153796	12/2008	Rabner	N/A	N/A
2009/0228299	12/2008	Kangarloo et al.	N/A	N/A
2009/0244484	12/2008	Sharifzadeh	351/221	A61B 5/0059
2010/0097576	12/2009	Witt et al.	N/A	N/A
2011/0116039	12/2010	Dai	351/205	A61F 9/00804
2011/0202017	12/2010	Reimer	N/A	N/A
2013/0100410	12/2012	Liang	N/A	N/A
2014/0126700	12/2013	Gertner et al.	N/A	N/A
2014/0129259	12/2013	Seriani	N/A	N/A
2016/0098528	12/2015	Seriani	N/A	N/A
2016/0128560	12/2015	Lee et al.	N/A	N/A
2016/0198943	12/2015	Lai	N/A	N/A
2016/0262617	12/2015	Gerrans	N/A	N/A
2016/0310000	12/2015	Meneghini	N/A	N/A
2016/0317025	12/2015	Lee et al.	N/A	N/A
2016/0338583	12/2015	Uchida	N/A	N/A
2017/0007111	12/2016	Samec et al.	N/A	N/A
2017/0027436	12/2016	Lee et al.	N/A	N/A
2017/0027444	12/2016	Rege et al.	N/A	N/A
2017/0027445	12/2016	Isogai	N/A	N/A
2017/0060399	12/2016	Hough et al.	N/A	N/A

2017/0061698	12/2016	Luebke et al.	N/A	N/A
2017/0100031	12/2016	Lai	N/A	N/A
2017/0135572	12/2016	Takii et al.	N/A	N/A
2017/0156591	12/2016	Berestka et al.	N/A	N/A
2017/0188811	12/2016	Lee	N/A	N/A
2017/0227771	12/2016	Sverdrup	N/A	G02B 5/289
2017/0269358	12/2016	Luebke et al.	N/A	N/A
2017/0311796	12/2016	Walsh et al.	N/A	N/A
2017/0325675	12/2016	Liu et al.	N/A	N/A
2018/0070820	12/2017	Fried et al.	N/A	N/A
2018/0078134	12/2017	Katz et al.	N/A	N/A
2018/0092525	12/2017	Lai	N/A	N/A
2018/0192872	12/2017	Fried et al.	N/A	N/A
2018/0256022	12/2017	Takii	N/A	A61B 3/0091
2019/0239790	12/2018	Gross et al.	N/A	N/A
2020/0029811	12/2019	Fried et al.	N/A	N/A
2020/0359891	12/2019	Fried et al.	N/A	N/A
2020/0405148	12/2019	Tran	N/A	N/A
2021/0011553	12/2020	Lussier et al.	N/A	N/A
2021/0015364	12/2020	Rege et al.	N/A	N/A
2021/0022603	12/2020	Predham et al.	N/A	N/A
2021/0051407	12/2020	Spector	N/A	N/A

FOREIGN PATENT DOCUMENTS

Patent No.	Application Date	Country	CPC
WO2005077256	12/2004	WO	N/A
WO2006061480	12/2005	WO	N/A
WO2011034638	12/2010	WO	N/A
WO2013105915	12/2012	WO	N/A
WO2014074157	12/2013	WO	N/A

Primary Examiner: Hasan; Mohammed A

Attorney, Agent or Firm: Springer Patents, LLC

Background/Summary

CROSS-REFERENCE TO RELATED APPLICATION (1) This patent application is a continuation of U.S. patent application Ser. No. 17/715,457, filed on 7 Apr. 2022, which is a continuation of U.S. patent application Ser. No. 17/321,409, filed on 15 May 2021, now U.S. Pat. No. 11,324,400, and claims priority under 35 U.S.C. § 119(e) from U.S. provisional patent application 63/048,946 filed on 7 Jul. 2020 in the name of Thomas D. Raymond et al., the entirety of each of which applications is hereby incorporated by reference herein as if fully set forth herein.

BACKGROUND
(1) In 2019, only about half of the people in the United States completed their recommended annual vision examination for a variety of reasons including inconvenience, lack of transportation, lack of awareness of eye health issues, and the high cost of eyeglasses; this in spite of the fact that 93 million adults in the United States are at high risk of vision loss.
(2) Similar trends are found internationally. In China, Japan, and Singapore less than one third of

patients receive annual comprehensive eye exams despite the fact that an epidemic level of myopia progression in the Asia Pacific region poses a significant threat of visual impairment.

(3) Furthermore, this rate may decline substantially in the future given the perceived risks of infection associated with routine eye examinations, especially in view of the worldwide COVID-19 pandemic and other possible future pandemics. Risks are present through hand, body, and facial contact with multiple ophthalmic instruments and chairs, and from the close proximity to technicians and to other subjects or patients in the waiting room.

(4) During the pandemic, the American Academy of Ophthalmology and the American Society of Retina Specialists recommended ophthalmologists restrict seeing patients to urgent and emergency cases and to screen incoming patients for the novel coronavirus. In the eye clinic, multiple traditional ophthalmic instruments are used in an eye exam, each requiring patient contact and thorough decontamination between patients. Patient workflow is reduced by clinical floor space limitations that have driven most practices to tightly pack the necessary multiple instruments into small examination rooms that are inherently inconsistent with social distancing. The reduced patient workflow and the additional burden from implementing necessary protocols to see patients have added to an already overly burdened patient workflow and serve to increase stress on health care providers (HCPs).

(5) Post-COVID-19 pressures will be significant on Health Care Providers (HCPs) as well. As the ratio of practitioners to patients diminishes, these practices will need to be ever more efficient to handle the increasing burden of eye care. These constraints immediately disqualify virtually all traditional single-purpose ophthalmic instruments and clearly beg for a new eye examination paradigm for this new era.

(6) Fortunately, ophthalmology has been a national leader in telemedicine augmented by technology and artificial intelligence. On Mar. 30, 2020, the U.S. Centers for Medicare & Medicaid Services released temporary regulatory waivers and issued new rules for virtual visits using online applications for billable telemedical services. In an April 2020 survey of 1300 eye HCPs, 88% indicated that they already offer remote medical examinations, mostly through phone-based consultations, and 56% indicated that they had billed for telehealth services in the previous week.

(7) However, existing telemedicine approaches can only capture a subset of the tests required for a full eye exam. For example, while visual acuity testing is possible without special equipment and can be used to verify a patient's current refractive prescription, without a refraction measurement it is not possible to alter that prescription or to provide a new patient a prescription. A refraction measurement typically requires refractive hardware and a skilled technician to operate it, hence tele-refraction is rarely available. For this reason, only 1.8% of those eye HCPs offer remote refractions. Finally, when asked "What would help you now?" the number one HCP response (64%) was "How to gear back up when re-opening."

(8) Furthermore, even if/when the COVID-19 pandemic subsides, there will continue to be a need for unattended and/or remotely-controlled eye examination equipment, for example to meet the eyecare needs in third world and developing countries and in remote and rural areas where access to in-person treatment is difficult. Also, in the case of unattended remote kiosks, prevention or minimization of contamination of the equipment is especially important as there may be no one available to clean, decontaminate or sterilize the equipment with any frequency.

(9) Accordingly, it would be desirable to provide a system and method for automated, non-contact, eye examination.

SUMMARY

(10) As disclosed herein an apparatus comprises: a processing system including a user interface; an eye measurement system including an optical system, wherein the eye measurement system is configured to make at least one optical measurement of an eye of a subject; a housing having the eye measurement system disposed therein, wherein the housing includes an aperture for providing light to and from the optical system and the eye while the subject is separated and spaced apart

from the housing and while the eye is not maintained in a fixed positional relationship with respect to the housing; an optical system movement arrangement which is configured to move the optical system; and an automatic eye tracking arrangement which is configured to ascertain a current positional relationship of the eye with respect to the optical system without human assistance, and in response thereto to control the optical system movement arrangement to move the optical system into a predetermined positional relationship with respect to the eye without human assistance. The eye measurement system includes: at least one objective refractive measurement device which is configured to make an objective refraction measurement of the eye via the optical system, a target, and a mirror system disposed in an optical path between the eye and the target for extending a length of the optical path, wherein the optical path further comprises at least one optical element of the optical system. The processing system is configured to interact with the subject via the user interface and in response to the interaction to adjust at least one parameter of the optical system to make a subjective refraction measurement of the eye based on the subject viewing the target.

(11) In some embodiments, the housing conforms to 3 A sanitary standards.

(12) In some embodiments, the housing comprises an anti-microbial material disposed at an exterior surface thereof.

(13) In some embodiments, the optical system movement arrangement is configured to move the optical system in two dimensions.

(14) In some embodiments, the optical system movement arrangement is configured to move the optical system in three dimensions.

(15) In some embodiments, the optical system includes a first lens, and the automatic eye tracking arrangement includes a Lidar device which is configured to provide light to the eye via the first lens and to receive returned light from the eye via the first lens for determining a distance between the eye and the first lens.

(16) In some versions of these embodiments, the optical system includes a pre-compensation section which is configurable to bring the target into focus on the subject's eye for making the subjective refraction measurement of the subject's eye, and the distance between the eye and the first lens as determined by the Lidar device is employed to adjust a position of at least one lens in the pre-compensation section to maintain focus and refractive correction for the eye.

(17) In some embodiments, the automatic eye tracking arrangement comprises: at least one light source configured to illuminate the eye; and at least one camera configured to receive an image of the eye, wherein the camera is configured to output image data of the image of the eye to the processing system, and wherein the processing system is configured to control the optical system movement arrangement to move the optical system into the predetermined positional relationship with respect to the eye based on the image data.

(18) In some embodiments, the apparatus includes a communication device, wherein the communication device is configured to communicate eye measurement data from the apparatus to an external remote terminal for evaluation.

(19) In some versions of these embodiments, the communication device is configured to communicate the eye measurement data from the apparatus to the external remote terminal via the Internet.

(20) In some versions of these embodiments, the processing system is configured to execute a filtration algorithm for filtering the eye measurement data prior to communication to the external remote terminal to reject at least a portion of the eye measurement data when the portion of the eye measurement data is taken when the automatic eye tracking arrangement has not aligned the optical system to the eye within a specified level of accuracy.

(21) In some versions of these embodiments, the apparatus, further comprises: at least one light source configured to illuminate the eye; and at least one camera configured to capture images of the eye, wherein the processing system is configured to execute a filtration algorithm for filtering the eye measurement data prior to communication to the external remote terminal to reject at least a

portion of the eye measurement data when the portion of the eye measurement data is taken when the images of the eye fail to meet predefined quality criteria due to at least one of: a full blink, a partial blink, an incorrect gaze angle, incomplete dis-accommodation, and a saccade.

(22) In some embodiments, the optical system includes a pre-compensation section which is configurable to bring the target into focus on the subject's eye for making the subjective refraction measurement of the subject's eye.

(23) In some versions of these embodiments, the pre-compensation section comprises one of: a set of discrete lenses, a Badal Optometer, Badal Optometer with Stokes cell, a variable focal length lens, a phase-only spatial light modulator, a deformable mirror and a retroreflection refractometer.

(24) In some versions of these embodiments, the pre-compensation section comprises the phase-only spatial light modulator, and the phase-only spatial light modulator is configured to compensate for tilt which is introduced by head and eye motion by the subject.

(25) In some embodiments, the at least one objective refractive measurement device includes one of: a Shack-Hartmann wavefront detector, a phase diversity sensor, a pyramid sensor, a curvature sensor, a point spread function (PSF) sensor, and a retro illumination refractometer.

(26) In some embodiments, the apparatus further comprises a display device provided at an external surface of the housing, wherein the display device is configured to provide information messages to at least one of the subject and an observer within sight of the display device.

(27) In some embodiments, the at least one optical measurement of the eye includes at least one of: a high order aberration of the eye, a pupil response characteristic, an external image of the eye, intraocular pressure of the eye, a fundoscope image of the eye, a corneal topography of the eye, an optical coherence tomography of the eye, and a blink rate of the eye.

(28) In some embodiments, the apparatus further comprises a slit lamp illumination source for enabling a slit lamp examination of the eye.

(29) In some embodiments, the apparatus further comprises a structured lighting device, wherein the structured lighting device is configured for at least one of: eye imaging, keratometry, eye motility testing, and slit lamp imaging of the eye.

(30) In some embodiments, the structured lighting comprises a plurality of light-emitting diodes arranged in a pattern around the aperture.

(31) In some embodiments, the structured lighting comprises a video display device.

(32) In some embodiments, the structured lighting includes at least one Helmholtz-like back-lit aperture.

(33) In some embodiments, the user interface includes at least a microphone for receiving voice communication from the subject, and a speaker for providing audio information to the subject.

(34) In some embodiments, the user interface includes at least one camera capturing images of at least a portion of the eye, and an algorithm executed by the processing system for processing the captured images, for identifying at least one of eye blinks and gestures of the subject in the captured images, and for interpreting the at least one of the eye blinks, fixation gaze angle, facial and hand gestures as conscious feedback from the subject. Additional unconscious cues such as squinting, and pupil dilation may also be used advantageously in interacting with the patient.

(35) In some embodiments, the user interface includes a camera for capturing images of the subject and a display device for displaying images to the subject.

(36) In some embodiments, the apparatus further comprises: at least one light source configured to illuminate the eye; at least one camera configured to capture images of the eye; and a visual cue generator for presenting to the subject a visual cue for changing a gaze angle of the eye while capturing the images of the eye.

(37) In some versions of these embodiments, the camera is configured to capture partial fundoscope images of a plurality of different portions of the eye at a corresponding plurality of different gaze angles, and the processing system is configured to stitch together the partial fundoscope images to produce a composite fundoscope image of the eye.

(38) In some embodiments, the apparatus further comprises an air movement device which is configured to remove and dispose of airborne pathogens so as to prevent the airborne pathogens from contaminating the apparatus.

(39) As also disclosed herein, an apparatus comprises: a processing system including a user interface; an eye measurement system including an optical system, wherein the eye measurement system is configured to make at least one optical measurement of an eye of a subject; a housing having the eye measurement system disposed therein, wherein the housing includes an aperture for providing light to and from the optical system and the eye while the subject is separated and spaced apart from the housing and while the eye is not maintained in a fixed positional relationship with respect to the housing; an optical system movement arrangement which is configured to move the optical system; an automatic eye tracking arrangement which is configured to ascertain a current positional relationship of the eye with respect to the optical system, and in response thereto to control the optical system movement arrangement to move the optical system into a predetermined positional relationship with respect to the eye; and a communication device, wherein the communication device is configured to communicate eye measurement data from the apparatus to an external remote terminal for evaluation. The eye measurement system includes: at least one objective refractive measurement device which is configured to make an objective refraction measurement of the eye via the optical system, a target, and a mirror system disposed in an optical path between the eye and the target for extending a length of the optical path, wherein the optical path further comprises at least one optical element of the optical system. The processing system is configured to interact with the subject via the user interface and in response to the interaction to adjust at least one parameter of the optical system to make a subjective refraction measurement of the eye based on the subject viewing the target. The communication device is further configured to receive instructions from the external remote terminal for adjusting at least one operating parameter of the apparatus.

(40) As further disclosed herein, a method comprises: making at least one optical measurement of an eye of a subject with an eye measurement system including an optical system, wherein the eye measurement system is disposed within a housing, wherein the housing includes an aperture for providing light to and from the optical system and the eye while the subject is separated and spaced apart from the housing and while the eye is not maintained in a fixed positional relationship with respect to the housing; and ascertaining, via an automatic eye tracking arrangement without human assistance, a current positional relationship of the eye with respect to the optical system, and in response thereto moving the optical system into a predetermined positional relationship with respect to the eye without human assistance. Making the at least one optical measurement of the eye includes: making an objective refraction measurement of the eye via the optical system, and interacting with the subject via a user interface, and in response to the interaction adjusting at least one parameter of the optical system to make a subjective refraction measurement of the eye based on the subject viewing a target through an optical path which includes a mirror system between the eye and the target for extending a length of the optical path, wherein the optical path further comprises at least one optical element of the optical system.

(41) As still further disclosed herein, a method comprises: making at least one optical measurement of an eye of a subject with an eye measurement system including an optical system, wherein the eye measurement system is disposed within a housing, wherein the housing includes an aperture for providing light to and from the optical system and the eye while the subject is separated and spaced apart from the housing and while the eye is not maintained in a fixed positional relationship with respect to the housing; and ascertaining, via an automatic eye tracking arrangement, a current positional relationship of the eye with respect to the optical system without necessary intervention from a human other than the subject, and in response thereto moving the optical system into a predetermined positional relationship with respect to the eye without necessary intervention from a human other than the subject. Making the at least one optical measurement of the eye includes:

making an objective refraction measurement of the eye via the optical system, and interacting with the subject via a user interface and in response to the interaction adjusting at least one parameter of the optical system to make a subjective refraction measurement of the eye, without necessary intervention from a human other than the subject, based on the subject viewing a target through an optical path which includes a mirror system between the eye and the target for extending a length of the optical path, wherein the optical path further comprises at least one optical element of the optical system.

(42) As yet further disclosed herein, a method, comprises: making at least one optical measurement of an eye of a subject with an eye measurement system including an optical system, wherein the eye measurement system is disposed within a housing, wherein the housing is disposed within an examination room, and wherein the housing includes an aperture for providing light to and from the optical system and the eye while the subject is separated and spaced apart from the housing and while the eye is not maintained in a fixed positional relationship with respect to the housing; and ascertaining, via an automatic eye tracking arrangement, a current positional relationship of the eye with respect to the optical system, and in response thereto moving the optical system into a predetermined positional relationship with respect to the eye without a presence of an ophthalmic technician in the examination room. Making the at least one optical measurement of the eye includes: making an objective refraction measurement of the eye via the optical system without the presence of the ophthalmic technician in the examination room, and interacting with the subject via a user interface and in response to the interaction adjusting at least one parameter of the optical system to make a subjective refraction measurement of the eye, without the presence of the ophthalmic technician in the examination room, based on the subject viewing a target through an optical path which includes a mirror system between the eye and the target for extending a length of the optical path, wherein the optical path further comprises at least one optical element of the optical system.

(43) As even further disclosed herein, a method, comprises: making at least one optical measurement of an eye of a subject with an eye measurement system including an optical system, wherein the eye measurement system is disposed within a housing, wherein the housing includes an aperture for providing light to and from the optical system and the eye while the subject is separated and spaced apart from the housing and while the eye is not maintained in a fixed positional relationship with respect to the housing; and ascertaining, via an automatic eye tracking arrangement, a current positional relationship of the eye with respect to the optical system, and in response thereto moving the optical system into a predetermined positional relationship with respect to the eye. Making the at least one optical measurement of the eye includes: making an objective refraction measurement of the eye via the optical system, and interacting with the subject via a user interface and in response to the interaction adjusting at least one parameter of the optical system to make a subjective refraction measurement of the eye based on the subject viewing a target through an optical path which includes a mirror system between the eye and the target for extending a length of the optical path, wherein the optical path further comprises at least one optical element of the optical system. The method also includes: communicating eye measurement data from the apparatus to an external remote terminal for evaluation; and receiving instructions from the external remote terminal for adjusting at least one operating parameter of the eye measurement system.

(44) As yet even further disclosed herein an apparatus comprises: a processing system including a user interface; an eye measurement system including an optical system, wherein the eye measurement system is configured to make at least one optical measurement of an eye of a subject; a housing having the eye measurement system disposed therein, wherein the housing includes an aperture for providing light to and from the optical system and the eye while the subject is separated and spaced apart from the housing and while the eye is not maintained in a fixed positional relationship with respect to the housing; an optical system movement arrangement which

is configured to move the optical system; and an automatic eye tracking arrangement which is configured to ascertain a current positional relationship of the eye with respect to the optical system without a presence of an ophthalmic technician in the examination room, and in response thereto to control the optical system movement arrangement to move the optical system into a predetermined positional relationship with respect to the eye without a presence of an ophthalmic technician in the examination room. The eye measurement system includes: at least one objective refractive measurement device which is configured to make an objective refraction measurement of the eye via the optical system, a target, and a mirror system disposed in an optical path between the eye and the target for extending a length of the optical path, wherein the optical path further comprises at least one optical element of the optical system. The processing system is configured to interact with the subject via the user interface and in response to the interaction to adjust at least one parameter of the optical system to make a subjective refraction measurement of the eye based on the subject viewing the target.

(45) As yet even further disclosed herein an apparatus comprises: a processing system having a user interface; an eye measurement system including an optical system, wherein the eye measurement system is configured to make at least one optical measurement of an eye of a subject; a housing having the eye measurement system disposed therein, wherein the housing includes an aperture for providing light to and from the optical system and the eye while the subject is separated and spaced apart from the housing and while the eye is not maintained in a fixed positional relationship with respect to the housing; an optical system movement arrangement which is configured to move the optical system; and an automatic eye tracking arrangement which is configured to ascertain a current positional relationship of the eye with respect to the optical system without necessary intervention from a human other than the subject, and in response thereto to control the optical system movement arrangement to move the optical system into a predetermined positional relationship with respect to the eye without necessary intervention from a human other than the subject. The eye measurement system includes: at least one objective refractive measurement device which is configured to make an objective refraction measurement of the eye via the optical system, a target, and a mirror system disposed in an optical path between the eye and the target for extending a length of the optical path, wherein the optical path further comprises at least one optical element of the optical system. The processing system is configured to interact with the subject via the user interface and in response to the interaction to adjust at least one parameter of the optical system to make a subjective refraction measurement of the eye based on the subject viewing the target.

Description

BRIEF DESCRIPTION OF THE DRAWINGS
(1) The example embodiments are best understood from the following detailed description when read with the accompanying drawing figures. Wherever applicable and practical, like reference numerals refer to like elements.
(2) FIG. **1** illustrates a portion of an example embodiment of an automated non-contact eye examination apparatus for examining the eye of a subject.
(3) FIG. **2** illustrates another portion of an example embodiment of an automated non-contact eye examination apparatus.
(4) FIG. **3** illustrates an embodiment of an eye measurement system which may be included in an eye examination apparatus.
(5) FIG. **4** illustrates an example embodiment of an optical system which may form part of an optical path for an eye measurement system.
(6) FIG. **5** illustrates an example embodiment of an eye alignment arrangement.

(7) FIG. **6** illustrates elements of an example embodiment of an autorefractor.

(8) FIG. **7** illustrates some principles of a pre-compensation section of an eye measurement system.

(9) FIG. **8***a*, FIG. **8***b* and FIG. **8***c* illustrate an example embodiment of a pre-compensation section of an eye measurement system.

(10) FIG. **9** illustrates an example embodiment of an operation of a focus loop of the pre-compensation section of FIG. **8**.

(11) FIG. **10** illustrates an example embodiment of an operation of a refraction correction loop of the pre-compensation section of FIG. **8**.

(12) FIG. **11** illustrates an example embodiment of a pre-compensation section of an eye measurement system which is provided with a Light Detection and Ranging ("LIDAR") device.

(13) FIG. **12** illustrates an external eye examination system using light sources to provide illumination of the eye.

(14) FIG. **13** illustrates an example embodiment of a structured lighting arrangement which may be used to illuminate the eye and to create new fixation directions to facilitate ocular measurements.

(15) FIG. **14** illustrates an example embodiment of a slit lamp illuminator of an eye measurement system.

(16) FIG. **15** shows a bottom view of the slit lamp illuminator of FIG. **14**.

(17) FIG. **16** illustrates how an example embodiment of an eye measurement system may obtain a fundus image of an eye.

(18) FIG. **17** illustrates an example of a fundus image of an eye.

(19) FIG. **18** is a flowchart of an example embodiment of a method of automated non-contact eye examination.

(20) FIG. **19** illustrates an example of a web page which may be displayed on a subject's cell phone before, during and/or after an interaction with an eye examination apparatus.

(21) FIG. **20** illustrates an example embodiment for a workflow for an eye examination of an eye.

(22) FIG. **21** illustrates an example embodiment for a workflow for an eye examination apparatus to make a subjective (manifest) refraction measurement of an eye.

(23) FIG. **22** illustrates an example embodiment of an eye target which may be used to communicate with a subject.

DETAILED DESCRIPTION

(24) In the following detailed description, for purposes of explanation and not limitation, example embodiments disclosing specific details are set forth in order to provide a thorough understanding of an embodiment according to the present teachings. However, it will be apparent to one having ordinary skill in the art having had the benefit of the present disclosure that other embodiments according to the present teachings that depart from the specific details disclosed herein remain within the scope of the appended claims. Moreover, descriptions of well-known apparati and methods may be omitted so as to not obscure the description of the example embodiments. Such methods and apparati are clearly within the scope of the present teachings.

(25) FIG. **1** illustrates a portion of an example embodiment of an automated non-contact eye examination instrument or apparatus **1000** for performing an eye examination of one or both eyes **15** of a patient or subject **10**. Apparatus **1000** includes a housing **1100**. As described in greater detail below, housing has an aperture **1110** for providing light to and from one or more internal optical systems and one or both eyes **15** of subject **10** while subject **10** is separated and spaced apart from housing **1100** and while eye **15** is not maintained in a fixed positional relationship with respect to housing **1100**. Here, an aperture may be defined as a space through which light passes between instrument or apparatus **1000** and one or both eyes **15** of subject **10**. In some embodiments, aperture **1110** may comprise a hole or opening in housing **1100**. In some embodiments, aperture **1110** may comprise a protective, light-transmissive or transparent, window through which light passes to and from one or more internal optical systems and one or both eyes **15** of subject **10**.

(26) Beneficially, the external surface of housing **1100** is smooth, allowing for quick and easy disinfection. Beneficially, the external surface of housing **1100** conforms to 3 A sanitary standards.

(27) In some embodiments, housing **1100** is provided with protective side shields **1120**.

(28) In some embodiments, an external surface of housing **1100** may be fabricated of, and/or coated with, an anti-microbial material.

(29) Apparatus **1000** further includes: cameras **1200**; at least one optical system **1300**; an optical system movement arrangement **1400**; an eye chart **1500** as a target for eye(s) **15** of subject **10**; and a mirror system **1600** disposed in an optical path between eye **15** of subject **10** and the eye chart **1500**. Mirror system **1600** lengthens an optical path between eye(s) **15** of subject **10** and eye chart **1500**, effectively providing a viewing lane for subject **10** to view eye chart **1500**, and accordingly may be referred to as a lane mirror arrangement. In some embodiments, apparatus **1000** may include two optical systems; one for each of the two eyes **15** of subject **10**. In some embodiments, apparatus **1000** may include two optical system movement arrangements **1400**; one for each optical system **1300** for each of a subject's two eyes **15**. In other embodiments, apparatus **1000** may include one optical system movement arrangement **1400** which moves two optical systems **1300**.

(30) FIG. **2** illustrates another portion of an example embodiment of an automated non-contact eye examination apparatus **2000**. Eye examination apparatus **2000** may be one embodiment of eye examination apparatus **1000** of FIG. **1**. FIG. **2** illustrates that eye examination apparatus **2000** includes optical system **1300**, a processing system **2200**, electronics **2300**, a display device **2400**, a speaker **2500**, a motor **2610** and a pulley **2620**. As with FIG. **1**, automated non-contact eye examination apparatus **2000** may include two optical systems; one for each of the two eyes **15** of subject **10**.

(31) Processing system **2200** may include one or more processors and memory, including volatile and/or non-volatile memory. The memory may store therein instructions which may be executed by the one or more processors to execute any of the various algorithms or methods disclosed below.

(32) Motor **2610** and pulley **2620** may comprises one embodiment of optical system movement arrangement **1400** of FIG. **1**.

(33) As shown in FIG. **2**, eye examination apparatus **2000** may communicate to one or more external remote terminals via Internet **50**. To that end, electronics **2300** may include a communication device (not shown) which may be wired and/or wireless and may communicate via WiFi, a wired Internet connection, a wireless mobile network (e.g., 4G or 5G), etc.

(34) Some of the significant features of eye examination apparatus **1000** include the easily disinfected smooth outer shell or housing **1100** and the notable absence of the traditional headrest for subject **10**. Eye measurement apparatus **1000** provides light to and from optical system **1300** and eye **15** of subject **10** while subject **10** is separated and spaced apart from housing **1100** and while eye **15** is not maintained in a fixed positional relationship with respect to housing **1100**.

(35) That is, in contrast to traditional ophthalmic instruments, eye examination apparatus **1000** does not require the head of subject **10** be constrained for eye measurements. Instead, eye examination apparatus **1000** includes an automatic eye tracking arrangement which is configured to ascertain a current positional relationship of eye **15** with respect to optical system **1300** (beneficially without human assistance), and in response thereto to control optical system movement arrangement **1400** to move optical system **1300** into a predetermined positional relationship with respect to eye **15** (again, beneficially without human assistance). The embodiment illustrated in FIG. **1** uses multiple cameras **1200** to automatically and continuously align the internal measurement modules (e.g., optical system **1300**) of eye examination apparatus **1000** to eye(s) **15** of subject **10** during the measurements, regardless of normal subject motion. This concept eliminates the need for subject **10** to contact any surfaces of eye examination apparatus **1000**, or to be in proximity to a technician during the measurements. Subject **10** does not even need to sit to have an eye examination.

(36) Inside outer shell **1100**, the use of spatial light modulators, a multi-function optical train, structured lighting, and head/eye tracking hardware may coordinate to provide subject **10** an

experience that an eye examination is as simple as reading eye chart **1500**. The optical paths for all measurements include a sufficiently large standoff, D.sub.STANDOFF, to allow all measurements to take place with subject **10** standing comfortably distant from the protective window of aperture **1110**. The eye measurement system may be capable of video rate captures of eye images and refraction measurements. Beneficially eye examination apparatus **1000** has a small footprint which allows multiple eye examination apparati **1000** to be co-located in the typically small examination rooms found in eye clinics.

(37) Audio/visual cues may be provided to the patient by the eye examination apparatus **1000** and/or remotely by a technician or physician prior to, during, and/or after the eye examination. The added optional feature of a remote telemedical connection may allow eye examination apparatus **1000** to be conveniently located at places where it can be easily accessed by patients or subjects, by pre-arranged appointment, during the course of their normal workday activities.

(38) In the United States, a complete eye examination requires the measurements and assessments shown in Table 1 below. Note that the Intraocular Pressure measurement is conducted to detect early-stage glaucoma, which may also be detected through fundoscopic examination.

(39) TABLE-US-00001 TABLE 1 Test/Function Module Reason/Diagnosis Objective Refraction Auto-refractor Detect uncorrected refractive error Subjective Refraction Pre-Compensator Refine refraction for prescription Visual Eye Display Tests spatial frequency response of central Acuity visual field Pupil Eye Imager Tests eye monocular and binocular eye Function response to light Confrontation Eye Imager Tests peripheral visual system response to Visual Fields moving objects Extraocular motility Eye Imager Tests stability of fixation and ability to and alignment smoothly track objects External (anterior) Eye Imager Detects pathologies of the eyelids and tissues Examination surrounding the eye, e.g., trachoma Slit Eye Imager Detects pathologies in the anterior segment Lamp Exam and cornea, e.g., corneal opacity, cataract Fundoscopic Fundus Imager Detects pathologies of the retina, e.g., Examination age-related macular degeneration, diabetic retinopathy Intraocular Pressure Tonographer Detects glaucoma

(40) In some embodiments, eye measurement apparatus **1000** is capable of performing all of the measurements and assessments listed in Table 1. In some embodiments, eye examination apparatus **1000** is capable of conducting remote refraction measurements without the presence of a technician, thus enabling corrective prescriptions for eyeglasses or contact lenses to be dispensed by a HCP immediately.

(41) FIG. **3** illustrates an embodiment of an eye measurement system **3000** which may be included in an eye examination apparatus such as eye examination apparatus **1000**.

(42) Eye measurement system **3000** includes a lane mirror system and an optical system **3500**, comprising optical devices and elements forming an optical path for eye measurement system **3000**. Optical system **3000** is a specific embodiment of optical system **1300** of FIGS. **1** and **2**.

(43) FIG. **4** illustrates an example embodiment of an optical system **3000** comprising various light sources, sensors (or detectors), viewing targets, mirrors and other various optical elements forming an optical path for eye measurement system **3000**. Optical system **3000** is a specific embodiment of optical system **3500** of FIG. **3**, and will be described in greater detail below.

(44) FIG. **3** shows the entire optical path including lane mirrors M**3**, M**4**, M**5** and M**6**, eye chart display device LS5. All lane mirrors may be mounted to housing **1100** so as to be stationary while LS5 is mounted to optical system **3500** that is free to move both vertically and horizontally as necessary to align itself to eye **15**. The lane length is the optical distance between Image Plane 2 (shown in FIG. **4**) and LS5. LS5 may be used to display traditional Snellen Eye Charts or similar targets upon which subject **10** may focus, as well as other icons or targets that may serve as fixation targets to manipulate the gaze angle of subject **10**. This optical arrangement allows the lane length to remain constant as optical system **3500** is translated vertically. The lane length may be comparable to that used in traditional clinical lanes; e.g., 3 m or longer. The lane mirrors are sufficiently wide (out of diagram plane) to reflect light from LS5 onto Image Plane 2 (and thus eye

15) regardless of the horizontal position of optical system **3500**. LS5 serves as the far refraction target traditionally used to measure the distance refraction correction of eye **15** during subjective refraction; it also acts as the fixation target during objective refraction measurement. Additionally, the lane mirrors and LS5 may serve both eyes **15** when eye examination apparatus **1000** is configured for binocular operation; such a configuration permits subject **10** to advantageously use convergence cues to perceive the target at full lane distance to reduce the likelihood of accommodation. An optional near target, LS6 (as shown in FIG. **4**), may be mounted onto optical system **3500** at a distance 30-50 cm from Image Plane 2; by translating mirror M**7** into the lane path, LS6 provides a near target for subjective and objective measurement of the near refraction correction for eyes **15** suffering from presbyopia.

(45) Eye examination apparatus **1000** addresses two areas of critical importance that offer technical challenges: automated alignment and tracking of eye **15** required to achieve the needed optical alignment without contacting subject **10**; and providing an optical configuration which has a sufficient optical standoff to permit robust isolation of eye examination apparatus **1000** and subject **10**.

(46) Regarding the former, in the past eye alignment has typically required the head of subject **10** to be constrained while the eye measurement system is brought to the desired object plane and the x and y positions (e.g., pupil center). The object plane of the optical system is typically designed to be fixed focus relative to the body of the apparatus. Alignment is achieved by monitoring the x and y positions of a desired fiducial while the z position is adjusted to bring the image into focus. Once alignment is achieved, one or a few measurement images may be captured (e.g., Shack-Hartmann wavefront images).

(47) In contrast, for embodiments of the automated eye examination apparatus **1000**, subject **10** is not required to be constrained and is subject to motion in 6 dimensions: three positions and three angles. However, rather than design the automated alignment and tracking system to apply alignment corrections of eye examination apparatus **1000** in all dimensions, in some embodiments, variance is accommodated in the z dimension through proper optical design. In this case, optical system **4000** may be already constrained to the distal side of the protective window of aperture **1110**. This may be accomplished through a variable focus component. In some embodiments, alignment cameras **1200** are capable of detecting and measuring z distance, cyclo-rotation, and gaze angle variations which can be used to compensate the measurements or to filter images from the video stream that exceed the desired tolerances. Note that the interpupillary distance must also be considered in this binocular instrument, however, this distance only need be adjusted at the start of the measurement sequence. With these choices, an automatic eye alignment and tracking system simplifies to correcting only lateral (x) and vertical corrections (y) while measuring the remaining 4 dimensions. The angle ranges measured are further bounded by providing a visual target for eye **15** to look at while being measured. Deviations may occur from saccadic movements which can be detected and excluded when necessary.

(48) In optical system **4000**, eye tracking may be accomplished through the inclusion of a Light Detection and Ranging ("LIDAR") device **4100** as described in greater detail below with respect to FIG. **11**.

(49) FIG. **5** illustrates another example embodiment of an eye alignment arrangement which incorporates cameras **1200**. This optical system uses two or more imaging cameras **1200** to provide 6-dimensional (e.g., x,y,z,α,β,χ) position and rotation information of the position of subject **10** relative eye examination apparatus **1000** to permit accurate, real-time alignment of optical system **3500** to subject **10**. Structured or unstructured lighting may optionally be supplied to improve the accuracy of the alignment. The two primary features to be tracked include the eye pupils. Cameras **1200** may be stationary with respect to eye examination apparatus **1000**, or may move with or independent of optical system **3500**. Cameras may optionally be equipped with prisms **5100** to increase the oblique angles that can be captured.

(50) Regarding the optical configuration, eye measurement system may include a variable phoropter/autorefractor, and an eye imaging arrangement including an imaging device (e.g., a camera) for imaging anterior and posterior segments of eye **15**.

(51) Manifest refraction is the gold standard for measuring refraction of eye **15**. FIG. **6** below illustrates an embodiment of eye examination apparatus which includes as a pre-compensation section **6100** a phoropter which comprises lenses that can be inserted into the line of sight of eye **15** while subject **10** views a distant object (e.g., Snellen eye chart at 4 meters distance). The physician may systematically vary the sphere value and the cylinder magnitude and axis while asking subject **10** to compare between lens combinations as to which is clearer. Such subjective refraction generally may be first done monocularly, but ultimately verified binocularly. To ensure that subject **10** has relaxed accommodation, additional plus lenses are often added to ensure the target becomes noticeably less focused. The lenses in the phoropter come in 0.25 Diopter increments, limiting the accuracy of measurement to what is typically achieved in eyeglasses and contact lenses. The repeatability of the measurement is limited to a standard deviation of 0.319 D by the subjective feedback and is highly dependent on the skill of the physician, particularly with respect to correcting the magnitude and axis of the cylinder component.

(52) FIG. **6** illustrates elements of an example embodiment of an autorefractor **6000**. Autorefractor **6000** includes, among other things, light source LS2, pre-compensation section **6100**, beam splitters **6102** and **6104**, a wavefront sensor **6200**, and lane mirror **6300**.

(53) In some embodiments, an autorefractor uses a Badal optometer as pre-compensation section **6100** through which subject **10** views an optical fixation target. The target is conveniently projected into eye **15** with a vergence at optical infinity or beyond (fogging) to stimulate subject **10** into relaxing accommodation as when viewing an actual object at a large distance. Light source LS2, having passed through the pre-compensation section and the anterior of the eye focuses onto the patient's retina and scatters backwards toward autorefractor **6000**. Sensor **6200** (e.g., a Shack-Hartmann wavefront detector, a phase diversity sensor, a pyramid sensor, a curvature sensor, a point spread function (PSF) sensor, a retro illumination refractometer, etc.) monitors the wavefront emanating from "guide star light" injected into eye **15** and scattering from the retina that passes through pre-compensation section **6100**, as discussed below with respect to FIGS. **7-11**. Calibrated pre-compensating section **6100**, such as a Badal optometer, in the sensing branch serves to subtract sphere and cylinder from the wavefront impinging on sensor **6200** such that it remains within its measurement range. The total wavefront from eye **15** is the sum of the pre-compensation values and the residual wavefront measured on sensor **6200**. With each successive measurement of the wavefront, the pre-compensation section **6100** may be adjusted to further reduce the wavefront curvature. This iterative process continues until the measured wavefront curvature it is within the desired tolerance; the process may then terminate and the final refraction reported. Measurement precision approaching 0.1 D is routinely obtained with properly designed autorefractors.

(54) While the auto refractor affords better precision than manifest refraction, traditional autorefractors seldom achieve the same level of accuracy as manifest refraction. The unnatural target projected at large optical distance does not effectively relax accommodation because other visual cues of distance are missing. In particular, the autorefractor is most often a monocular device that excludes convergence cues to distance; other cues can also make the subject perceive the target closer (e.g., looking into a small instrument or a small tube). These factors frequently lead to "instrument accommodation" that can amount to a large fraction of a diopter of error. The cylinder magnitude and axis, on the other hand, are very accurately measured by an autorefractor.

(55) In contrast to existing instruments, eye examination apparatus **1000** may support (simultaneous) manifest refraction and autorefraction measurements using the same optical system **1300**, and both can be combined to yield higher accuracy results. In some embodiments, autorefractor **6000** incorporates corrective lenses positioned at a variable optical standoff of 150-200 mm and a real, dynamically programmable target (on an electronic display) at a distance

presented to the subject in binocular format. The distant real target mitigates "instrument accommodation" by subject **10**. While similar to the manifest refraction set up, this innovative approach raises challenges because the refractive correction is placed far from the normal spectacle plane (about 12.5 mm from eye vertex) where phoropter lenses would be placed and may introduce unwanted, unnatural optical distortions (e.g., tilt). Fortunately, the mathematics of ray tracing is well established, and these distortions can be modelled and corrected. The corrective power of this pre-compensation section can be remotely adjusted in response to feedback from subject **10**. The refractive measurement from the autorefractor may be advantageously used to initially adjust the pre-compensation section prior to manifest refraction. With the final correction in place, the HCP can conduct traditional subjective visual acuity testing much as they would with a phoropter, except that the lens adjustment for this scenario is electronically controlled. In this way the advantages of the accuracy of a phoropter and manifest refraction can be combined with the precision of the autorefractor. Indeed, eye examination apparatus **1000** may deliver both subjective refraction (manifest refraction) and objective refraction (autorefraction) measurements.

(56) FIG. **7** illustrates some principles of a pre-compensation section of an eye measurement system.

(57) The effective focal length, fcp, when located at the correction plane, at distance CP from eye **15**, for a target at distance Lane, will bring the target into best focus on the retina of the dis-accommodated eye **15**.

(58) Equation 1 below shows how the RoC, the radius of curvature of the wavefront at the corneal vertex, is related to fcp, CP, and Lane; RoC is positive for hyperopes, negative for myopes, and infinity for a true emmetrope.

(59) $\frac{1}{f_{cp}} = \frac{1}{RoC + CP} + \frac{1}{\text{Lane}} = Rx_{cp}$ Equation1

(60) The measurement of ROC can be done at any convenient distance CP.

(61) Lane is typically >3 meters in most eye clinics.

(62) Given the ROC for each subject eye **15**, the physician prescribes refractive corrections, Rx.sub.cp, using Equation 1 with CP=0 for contact lenses and refractive surgeries, and to about 0.0125 meters for eyeglasses.

(63) The purpose of the pre-compensation section is to compensate the subject's refractive error (sphero-cylindrical) so the subject sees the target clearly. The effective focal length, f.sub.cp, of the pre-compensation section is adjusted to bring the target into focus when eye **16** is dis-accommodated. Dis-accommodation may be accomplished by manually fogging (as in manifest refraction) or with an interactive algorithm (as in autorefractors). When eye **15** is dis-accommodated and the sphero-cylindrical correction of the pre-compensation section has been adjusted to produce best focus of the target for the subject, the radius of curvature (RoC) of the wavefront meridians just outside the cornea can be determined mathematically. The measured RoCs can then be used to prescribe the appropriate sphero-cylindrical refractive correction (e.g., contact lenses, eyeglasses, or refractive surgery) for subject **10**.

(64) Various embodiments of pre-compensation may be accomplished with a variety of techniques. In its simplest embodiment, the pre-compensation section may comprise a collection of lenses much like in a phoropter. Other embodiments include the incorporation of variable power pre-compensation elements such as variable focal length lenses (e.g., liquid lenses), a wide angle Badal optometer that employs moving optics on linear stages, variable mirrors (e.g., adaptive optics deformable mirror), a phase only spatial light modulator, or a retroreflection refractor, or combinations of the above.

(65) In one such embodiment, a phase only spatial light modulator (SLM) may be coupled with helper lenses to the same effect but with higher speed and with the ability to pre-compensate cylinder at any axis. The SLM is capable of providing variable spherocylindrical correction over some dynamic range (e.g., ±5 D), which can be added to the helper lens(es) to span the relevant

refractive correction range of human eyes (−16 to +8 D sphere, and 0 to −6 D cylinder). Like the variable power options which act to reduce the number of corrective lenses and mechanical complexity while improving the resolution of measurement below 0.25 diopters, the SLM introduces the ability to also correct for unwanted distortions such as tip/tilt as the subject moves laterally. These variable power options also can compensate for subject motion that introduces variations in the optical standoff which would otherwise affect the measurement.

(66) SLMs generally only supply about a 2π of phase delay but can do so at spatial resolutions approaching 4160(h)×2464(v) using 3.45 μm pixels at refresh rates approaching 60 Hz. With this density, it is possible to create a variable power Fresnel lens with sphero-cylinder power up to ±5 diopters over a 6 mm diameter aperture. Furthermore, the center of this correction can be rapidly shifted to compensate for lateral eye movement. The high refresh rate permits the apparent compensation of chromatic aberration normally attributed to diffractive lenses when used with polychromatic targets. Color field sequential display rapidly sequentially displays the primary colors in the target while the subject views through corresponding corrected diffractive patterns; color fusion is accomplished in the human visual system.

(67) The final power of the pre-compensating element can be mathematically converted into a prescription for eyeglasses, contact lenses or refractive surgery using simple paraxial ray tracing formulas like Equation 1.

(68) Returning to FIG. **4**, FIG. **4** shows the schematic diagram of the optical path of eye measurement system **3000**. Eye **15** is shown at the far left.

(69) Light from light sources LS1, LS2, LS3, or LS4 may illuminate eye **15** and create reflected and scattered light that travels toward eye measurement system **3000** entering through aperture or window W1. L1 captures this light and fully or partially collimates it for analysis. Light travels through BS1 which may preferentially reflect wavelengths longer than 900 nm and/or may be designed to preferentially reflect S polarized light; BS2 may transmit shorter wavelengths. As discussed in greater detail below with respect to FIGS. **8**-**11**, optical system **4000** includes a relay imager comprising lenses L1 and L2 and a Badal optometer comprising lenses L3 and L4 as a pre-compensation section which is configurable to bring the target into focus on eye **15** for making the subjective refraction measurement of the subject's eye **15**.

(70) LIDAR device **4100** may be fixed to lens L1; L1 may move to bring the relay imager into focus. L2 is the second lens of the relay imager and this focusses the light from eye **15** onto a two-dimensional imaging sensor or camera IM1, positioned at Image Plane 1. BS2 is a partial reflector that allows light from eye **15** to reach IM1 to complete the eye imaging section of optical system **4000**.

(71) The light reflected by BS2 travels through a Stokes Cell ("SC"), which allows for continuously adjustable astigmatic correction; SC is positioned at Image Plane 1a which is equidistant from BS2 as Image Plane 1. Spherical correction is accomplished with the Badal optometer comprised of lenses L3 and L4 and mirrors M**1** and M**2**. Mirrors M**1** and M**3** can be translated simultaneously to change the distance between L3 and L4, thereby providing continuously adjustable spherical correction. BS3 is also a partial reflector for visible light and a high reflector for near infrared (NIR) light. The transmitted visible light allows subject **10** to view the eye chart; Image Plane 2 represents the optical position of eye **15**, with refractive correction applied, when viewing the targets LS5 or LS6. The remaining visible and NIR light may be directed toward a wavefront or similar sensor; a point spread function (PSF) sensor is shown in FIG. **4**. Light is focused by lens L6, positioned at Image Plane 2a (equidistant from BS3 as Image Plane 2) onto imaging sensor IM2; the size and shape of the formed spot can be analyzed to advantageously to drive the Stokes Cell and Badal optometer to correct for eye refractive errors.

(72) Imaging sensor IM2 measures the radius of curvature of the wavefront of light from eye **15** using well-known 'guide-star' techniques. Imaging sensor IM2 may include any of the following: a Shack-Hartmann Sensor, a Phase Diversity Sensor, a Pyramid Sensor, a Curvature Sensor, a point

spread function (PSF) Sensor, or a Retro-illumination refractometer. Additional lenses may be included as required to bring the scattered wavefront onto the imaging sensor IM2 for proper measurement.

(73) Light source LS2 may be a NIR super luminescent diode or LED that provides a narrow beam light (e.g., 2 mm diameter) collimated by lens L7 and can be used to create a tight spot on the retina of eye **15** to act as a "guide star." The output aperture for LS2 is positioned at Image Plane 2a to ensure that the light is imaged onto the Object Plane. LS3 is an alternate light source which may be divergent in contrast to that produced by LS2; it may be used to flood illuminate the retina when imaging the fundus. Like LS2, its output aperture may be approximately 2 mm and is positioned at Image Plane 2a. LS2 and LS3 may be physically translated into position or optically or electronically switched.

(74) FIGS. **8***a,* **8***b* and **8***c* illustrate an example embodiment of a pre-compensation section **8000** of an eye measurement system, including a relay imager **8100** and a Badal optometer **8200**.

(75) This configuration has the advantage of providing a sharp eye image to monitor eye alignment and the current eye state (e.g., open or closed eyelids) while measuring and providing a target with proper refractive correction to the subject. The target is not shown in FIG. **8** but would be to the right of the position labelled Image Plane 2. FIG. **8***a* illustrates the nominal lens positions for a nominal position of eye **15** relative to the optical system. FIG. **8***b* illustrates the lens positions when eye **15** is positioned further from the optical system than in FIG. **8***a*. FIG. **8***c* illustrates the lens positions when eye **15** is positioned closer to the optical system than in FIG. **8***a*. Note that the positions of lenses L2 and L3 do not change.

(76) In this embodiment, Relay Imager **8100** casts a sharp image of eye **15** at Image Plane 1 while Badal Optometer **8200** relays that image onto Image Plane 2 while also adjusting the wavefront curvature to as to compensate for the refractive error of eye **15**. Relay Imager **8100** consists of two lenses, L1 and L2 of focal length f1 and f2, respectively. Relay Imager **8100** will have its object plane a distance f1 from L1 and its image plane at a distance f2 from L2. This produces an image with fixed magnification −f2/f1 at Image Plane 1. The motion of eye **15** is tracked by translating lens L1 to maintain a distance of f1 to eye **15**, thus ensuring that a sharp image of eye **15** will always appear at Image Plane 1 independent of the position of eye **15** relative to the optical system. The distance between L1 and eye **15** may be maintained by actuating the position of L1 according to an autofocus algorithm or by direct measurement the distance by using a LIDAR device or other distance sensor.

(77) Badal Optometer **8200** similarly consists of two lenses, L3 and L4 with focal lengths f3 and f4. A continuous range of refractive correction may be applied to the wavefront curvature by adjusting the distance between L3 and L4. By advantageously placing an astigmatic correction device (e.g., a Stokes cell) at Image Plane 1, Badal optometer **8200** can correct for both spherical and cylindrical refractive errors.

(78) Relay Imager **8100** has the drawback that it may alter the wavefront curvature at Image Planes 1 and 2 depending on the separation between L1 and L2. However, this correction is deterministic and can be compensated through a small adjustment of the distance between L3 and L4 as shown in FIGS. **9** and **10**.

(79) FIG. **9** illustrates an example embodiment of an operation of a focus loop **9000** of the pre-compensation section of FIG. **8**. Focus loop **9000** may be implemented by software stored in memory and which is executed by a processor, such as by processing system **2200**.

(80) Operation **9100** includes reading the position of eye **15** from LIDAR device **4100**.

(81) Operation **9200** includes reading the current position of lens L1.

(82) Operation **9300** includes subtracting the positions obtains in operations **9100** and **9200** to obtain the eye-to-L1 distance.

(83) Operation **9400** includes reading f1 (focal length of lens L1) from calibration data.

(84) Operation **9500** includes subtracting f1 from the eye-to-L1 distance to obtain the tracking error

for the position of lens L1.

(85) Operation **9600** includes adding the tracking error to the current position of lens L1 to obtain a new target position for lens L1.

(86) Operation **9700** includes moving lens L1 to the new target position.

(87) Operation **9800** includes updating the current position of lens L1.

(88) Operation **9900** includes providing the updated current position of lens L1 to the refraction correction loop of FIG. **10**.

(89) FIG. **10** illustrates an example embodiment of an operation of a refraction correction loop **10000** of the pre-compensation section of FIG. **8**. Refraction correction loop **10000** may be implemented by software stored in memory and which is executed by a processor, such as by processing system **2200**.

(90) Operation **10100** includes reading the refraction error from a wavefront sensor.

(91) Operation **10200** includes calculating the refractive correction to the position of lens L4.

(92) Operation **10300** includes obtaining the position of lens L1 from the focus loop **9000**.

(93) Operation **10400** includes reading the position of lens L2 from calibration data.

(94) Operation **10500** includes calculating a focus correction to the position of lens L4 from the outputs of operations **10300** and **10400**.

(95) Operation **10600** includes reading the current position of lens L4.

(96) Operation **10700** includes adding the refraction correction and the focus correction to the current position of lens L4 to obtain a new target position for lens L4.

(97) Operation **10800** includes moving the lens L4 to the target position.

(98) Operation **10900** includes updating the current position of lens L4.

(99) FIG. **11** illustrates an example embodiment of a pre-compensation section **11000** of an eye measurement system which is provided with LIDAR device **4100**.

(100) The use of LIDAR device **4100** simplifies the control algorithm compared to an autofocus algorithm by reducing the calculations required in each control iteration. Compact LIDAR devices **4100** are commercially available with a range and distance accuracy compatible with such an embodiment. In this case, LIDAR device **4100** can be mounted to move with L1 to directly measure distance from L1 to eye **15**. LIDAR device **4100** may also be advantageously optically positioned at Image Plane 1 or 2 to employ the optical system to ensure that only light reflected from the cornea is used in the ranging. FIG. **11** illustrates how the light from LIDAR device **4100** may be collimated with lens L5 and sent through L1 to focus on the cornea. In this case, lens L5, beam splitter BS1, and the LIDAR unit may move with L1.

(101) FIG. **12** illustrates an external eye examination system **12000** using light sources to provide illumination of eye **15**, for example for capturing images of eye **15** using camera **12100**.

(102) Images of the exterior of eye **15** are useful for testing pupil function, external examination for pathologies of eye **15** and surrounding tissues, to test extraocular motility and alignment. Imaging of the anterior of eye **15** with appropriate lighting from lighting elements **12200** may permit some level of slit lamp examination. Finally, imaging of the posterior of eye **15** allows examination of the fundus. In some embodiments, each of these imaging systems could be independently designed and simply mounted at a different location in the eye alignment and tracking system

(103) Two or more cameras **12100** may supply video images of both eyes **15** to test pupil response, ocular motility, visual confrontation, and for external and internal examination of eyes **15** and nearby structures (e.g., eyelids).

(104) Different visual stimuli may be applied through peripheral or coaxial light sources for each examination element.

(105) Light sources **12200** may be fixed relative to the field of view or may move within it; some light sources may be structured (e.g., images of fingers, or a narrow bright slit); some may be arranged in an array, as described below with respect to FIG. **13**.

(106) In some embodiments, pre-compensation section **6100** of the optical system may be adjusted

to obtain magnified images of the internal or external area of eye **15**.

(107) In some embodiments, pre-compensation section **6100** may be used to produce an aerial image that is subsequently conditioned to match camera **12100**. The image can stay in focus despite changes in standoff distance; small magnification differences so introduced can be compensated in the display of the image and in the quantitative analyses as well. The use of additional light sources **12200** can not only illuminate eye **15** and surrounding tissue, but also can be used for keratometry and corneal topography if desired. Light sources **12200** can also provide stimuli to the subject for pupil and confrontation visual field and extraocular motility and alignment testing. In some cases, lighting **12200** may be controlled to smoothly translate across areas of the peripheral field of view of subject **10**. In a much similar way, slit lamp examination can be simulated with this same arrangement.

(108) FIG. **13** illustrates an example embodiment of a structured lighting arrangement **13000** which may be used to illuminate eye **15** and to create new fixation directions to facilitate ocular measurements.

(109) Structured lighting may be used to illuminate eye **15** and to create new fixation directions to facilitate ocular measurements. Each dot in FIG. **13** represents an individually addressable light source **13200**. The ring pattern around aperture **13100** may be symmetrically disposed around the optic axis of the optical system and may be used to illuminate eye **15** for eye imaging and/or for keratometric measurement. The array of peripheral light sources **13200** may be used for corneal topographic measurements and/or to test the integrity of the tear film surface when activated in concert, and/or can act as fixation points to change the gaze of subject **10** for slit lamp examination, for extraocular motility, and confrontation visual field testing.

(110) FIG. **14** illustrates an example embodiment of a slit lamp illuminator **14000** of an eye measurement system. The slit lamp illumination is from below eye **15** and utilizes a Kholer configuration. Light source LS4 is imaged onto projector lens L9 by condenser lens L8. The slit is created electronically on digital light processing chip, DLP, to form arbitrarily shaped apertures whose dimensions can be controlled electronically with approximately 10 μm resolution and which can be changed at video rates in synchrony with image captures on IM1, for example by processing system **2200**. The slit illuminator assembly also comprises a beam dump, BD**1**, which may absorb all unwanted light from LS4. This assembly is suspended above or below the LIDAR assembly and moves with the optic assembly **3500** to maintain alignment with the eye as it moves. The slit lamp illuminator assembly may also rotate about a vertical axis located at eye **15**, as shown in FIG. **15**, to allow an operator (e.g., a HCP controlling slit lamp illuminator from an external remote terminal via a communication device of eye examination apparatus **1000**) to change the angle of incidence continuously over a range of +60° from the optic axis. Fine positioning of the light image on eye **15** can be accomplished electronically with the DLP. The observation angle for the scattered light can be adjusted by using a selected LED on LS1 to create a fixation target upon which the subject can fixate, thereby rotating eye **15** and thus the observation angle.

(111) FIG. **15** shows a bottom view of the slit lamp illuminator of FIG. **14**.

(112) FIG. **16** illustrates how an example embodiment of an eye measurement system may obtain a fundus image of an eye.

(113) Equation 2 below may be applied with respect to FIG. **16**:

(114) $\frac{1}{f_{\text{fundus}}} = \frac{1}{RoC + CP} + \frac{1}{\text{Image}}$ Equation2

(115) In some embodiments, a fundus imager may invoke different gaze angles for subject **10** using structured lighting **13200** to attain multiple images with a small field of view which can be stitched together into a high field of view image of the fundus.

(116) Fundus imaging also may benefit from the pre-compensation section of the optical system, discussed above. In this case lighting is directed into eye **15** and knowledge of the refractive state of eye **15** may simplify maintaining focus. The case shown in FIG. **16** is essentially direct

ophthalmoscopy where the lighting is directed through the nodal point of eye **15** to illuminate a large section of the fundus. To obtain high angle coverage of the fundus, subject **10** may be stimulated to gaze in different directions with lighting that creates a moving target while images are captured continuously. Processing system **2200** may employ image processing to undistort the images and then use fundus landmarks to stitch them into a large field of view fundus image.

(117) FIG. **17** illustrates an example of a fundus image **17000** of eye **15** which may be obtained by eye examination apparatus **1000** and eye measurement system **3000** as discussed above with respect to FIG. **16**.

(118) In some embodiments, eye examination apparatus **1000** may include a tonographer (not shown), and in that case the presence and progression of glaucoma may be derived from tonographer measurements. In other embodiments, fundoscopy of eye **15** allows the eye examination apparatus **1000** to test for glaucoma of eye **15**. Examples of a technique for glaucoma detection from a fundus image are disclosed in Shilpa Sameer Kanse, et al., *"Retinal Fundus Image for Glaucoma Detection—A Review and Study,"* J. INTELL. SYST. 2017, the entirety of which is hereby incorporated by reference herein as if fully set forth herein.

(119) FIG. **18** is a flowchart of an example embodiment of a method **18000** of automated non-contact eye examination.

(120) An operation **18100** includes an eye examination apparatus ascertaining, via an automatic eye tracking arrangement, a current positional relationship of a subject's eye with respect to an optical system of an eye measurement system of the eye examination apparatus. Beneficially, this may be done without human assistance. In some embodiments, operation **18100** may track the positional relationships for both of a subject's eyes at the same time.

(121) An operation **18200** includes the eye examination apparatus providing light to and from the optical system and a subject's eye(s) while the subject is separated and spaced apart from the housing of the eye examination apparatus and while the eye is not maintained in a fixed positional relationship with respect to the housing. In some embodiments, operation **18200** may include providing light to and from the optical system to both of a subject's eyes at the same time. In some embodiments, the eye measurement system may have two separate optical systems for the subject's two eyes, and in that case operation **18200** may include providing light to and from each optical system to a corresponding one of the subject's eyes, for example at the same time.

(122) An operation **18300** includes controlling an optical system movement arrangement of the eye examination apparatus to move the optical system into a predetermined positional relationship with respect to the subject's eye(s). Beneficially, this may be done without human assistance. In some embodiments, the eye examination apparatus may have two separate optical systems for the subject's two eyes, and in that case operation **18300** may include moving each optical system into a predetermined positional relationship with respect to a corresponding one of the subject's eyes.

(123) An operation **18400** includes the eye examination apparatus making an objective refraction measurement of a subject's eye via the optical system. In various embodiments, operation **18400** may include making an objective refraction measurement of a subject's eye via a Shack-Hartmann wavefront detector, a phase diversity sensor, a pyramid sensor, a curvature sensor, a point spread function (PSF) sensor, a retro illumination refractometer, etc. In some embodiments, the eye measurement system may have two separate optical systems and object measurement devices for the subject's two eyes, and in that case operation **18400** may include the eye examination apparatus making an objective refraction measurement of each of the subject's eyes via a corresponding optical system.

(124) An operation **18500** includes the eye examination apparatus interacting with the subject via a user interface, and in response to the interaction adjusting at least one parameter of the optical system to make a subjective refraction measurement of the subject's eye(s) based on the subject viewing a target. Beneficially, the target may be an eye chart. Beneficially, subjective measurements may be made separately for each eye, and a combined subject measurement may be

made with the subject viewing the target with both eyes at the same time.

(125) An operation **18600** includes the eye examination apparatus making other measurements and/or examinations of the subject's eye via the optical system, or both eyes in parallel via corresponding optical systems for each eye. In various embodiments, these other measurements and/or examinations may include measuring high order aberrations of the eye, determining intraocular pressure, performing a fundoscopic examination, performing a slit lamp examination, determining keratometry/corneal topography/astigmatism, determining a pupil function, performing confrontation visual field testing (e.g., peripheral vision test), and/or determining extraocular motility. In some embodiments, operation **18600** may be omitted.

(126) An operation **18700** includes the eye examination apparatus qualifying/filtering eye measurement data. In some embodiments, eye measurement data may be filtered to reject at least a portion of the eye measurement data when the portion of the eye measurement data is taken when the automatic eye tracking arrangement has not aligned the optical system to the eye within a specified level of accuracy. In some embodiments, eye measurement data may be filtered to reject at least a portion of the eye measurement data when the portion of the eye measurement data is taken when the images of the eye fail to meet predefined quality criteria due to at least one of: a full blink, a partial blink, an incorrect gaze angle, incomplete dis-accommodation, and a saccade. In some embodiments, operation **18700** may be omitted.

(127) An operation **18800** includes communicating eye measurement data from the eye examination apparatus to an external remote terminal for evaluation, for example by a healthcare professional. The remote terminal may be a computer, a laptop, a tablet device, or even a cell phone. In some embodiments, the external remote terminal may be disposed in a different room than the eye examination apparatus. In some embodiments, the external remote terminal may be disposed in another building, another city, another state/province, or even another country than the eye examination apparatus. In some embodiments, the eye measurement data may be communicated via the Internet. In some embodiments, the eye measurement data may be communicated in real time, as it is processed by the eye examination apparatus. In some embodiments, the eye examination apparatus only communicates filtered eye measurement data which was filtered in operation **18700**.

(128) An operation **18900** includes the eye examination apparatus providing information messages via display device **2400** provided at an external surface of the housing to the subject and/or an observer who is within sight of the display device. In some embodiments, such information messages may include advertisements or commercials, which may be in the form of images or video.

(129) In some embodiments, advertisements may be displayed on display device **2440** on an external face of housing **1100** when eye examination apparatus **1000** is not in use. These advertisements can provide information about eye examination apparatus **1000**, can provide information about vision health insurance or other public services, or can simply be promotional material from paid sponsors. Furthermore, advertisements can be played on the internal display (see FIG. **22**) that is used for the subject visual target at any time during the examination. An example would be right after an objective refraction has been completed so that the refraction results can be used to ensure that the instrument will display the informational content in a clear fashion.

(130) In various embodiments, method **18000** may include additional operations to those shown in FIG. **18**. In some embodiments, the eye measurement apparatus may display a QR code (or bar code) with instructions on the video monitor instructing subject **10** to use their camera to sign up for an eye exam. The QR code or hyperlink that connects the potential subject with the instrument (or a network) in order to sign up for and potentially initiate the eye examination.

(131) In some embodiments, when before, during, and/or after a subject encounter with an eye examination apparatus, the subject supplies personal information, including identification

information, and may complete a patient intake survey. In some embodiments, this may be accomplished by providing the eye examination apparatus with a webserver which may interact with the subject's mobile phone, tablet or laptop. In some embodiments, a web service accessible via the internet which handles eye examination scheduling may provide these functions, rather than supplying each eye examination apparatus with a webserver.

(132) FIG. **19** illustrates an example of a web page which may be displayed on a subject's cell phone before, during and/or after an interaction with the eye examination apparatus.

(133) FIG. **20** illustrates an example embodiment for a workflow **20000** for an eye examination of an eye.

(134) FIG. **20** illustrates operations (**20010** and **20020**) which occur when the eye examination apparatus is located in an eyecare clinic, operations which occur when the eye examination apparatus is an unattended kiosk (**20110**, **20120** and **20130**), and operations which are common to both situations (all remaining operations).

(135) An operation **20010** includes an eye examination subject, or patient, checking in at the front office of an eye care clinic at the time of appointment.

(136) An operation **20020** includes leading the subject to the eye examination apparatus, and a health care professional (HCP) technician provides audio cues to look at a target in the eye examination apparatus.

(137) An operation **20110** includes an eye examination subject, or patient, walking up to a kiosk comprising an eye examination apparatus and checking in to the kiosk using a smartphone app, and initiating an eye examination.

(138) An operation **20120** includes a HCP logging onto a web portal via an external remote terminal.

(139) An operation **20210** includes the subject standing in front of instrument and receiving audio clues to look for the fixation target.

(140) An operation **20215** includes the eye examination apparatus detecting the presence of the subject, starting gross alignment with the subject's eye(s), and providing audio instructions to the subject.

(141) An operation **20220** includes auto-aligning an optical system to the correct height for the subject, performing fine alignment for interpupillary distance, estimating a working distance to the eye(s), and begin tracking the eye(s).

(142) An operation **20225** includes performing an initial objective measurement of refraction, pre-compensating the target path by correcting for the initially-measured refraction, making multiple refraction measurements of the eye(s), capturing images of the anterior pupil of each eye, and tracking eye motion and head motion while compensating the target path.

(143) An operation **20230** includes providing audio clues for the subject and moving the target.

(144) An operation **20235** includes the subject receiving instructions to watch a moving fixation target, and the subject watching the moving fixation target.

(145) An operation **20240** includes an unseen infrared (IR) illumination illuminating the fundus of the subject's eye(s) under a controlled sequence of gaze angles. Several images of different portions of the fundus may be processed and stitched together to build a larger image of the fundus.

(146) An operation **20245** includes the eye examination apparatus either being controlled by the HCP for a subjective refraction test (e.g., via a tablet device), or running an automated algorithm (kiosk implementation), with the subject responding to standard yes/no questions using voice recognition. Monocular subjective refraction for each eye may be determined.

(147) An operation **20250** includes a subject answering subjective questions about visual acuity for each eye, for example: "Which one is better? 1 or 2?"

(148) An operation **20255** includes the eye examination apparatus assembling eye measurement data or results and providing the assembled eye measurement data/results to the HCP, either via a clinic internal network or HIPAA web portal, and informing a subject and a remote HCP that the

eye examination has completed.

(149) An operation **20130** includes the HCP receiving patient data and the assembled eye measurement data/results.

(150) An operation **20260** includes the HCP reviewing the assembled eye measurement data/results (e.g., subjective vs objective refraction, fundus imaging, etc.) and deciding whether the subject needs a manual refraction or retinal examination.

(151) An operation **20265** includes the HCP discussing the eye examination results in person or over a web portal, and providing the subject with a prescription.

(152) An operation **20270** includes the HCP updating internal patient records with information from the eye examination, and potentially scheduling a follow-up eye examination.

(153) FIG. **21** illustrates an example embodiment for a workflow **21000** for an eye examination apparatus to make a subjective (manifest) refraction measurement of an eye.

(154) In FIG. **21**, the following applies: ss=increment step size; max=max tries; max.sub.OM=OverMinus tries; OR=Objective Refraction; CR=current refraction; FR=final refraction; Thresh=convergence threshold; OM thresh=over-minus threshold. In an example: beginning ss=1.0 D, cnt=0, cnt2=0 and beginning CR=OR.

(155) Workflow **21000** uses voice recognition and captures subject facial responses during a subjective refraction for post-measurement review by a Health Care Provider (HCP).

(156) The starting point for the subjective examination is after the eye examination apparatus has captured an objective refraction for the eye(s). The objective refraction may be used as the starting point for the subjective refraction measurement. The sphero-cylindrical compensation may be added to the target path (e.g., also accounting for chromatic aberrations and for lane length). Each choice may be briefly presented to the subject, e.g., for 3-5 seconds.

(157) An example in English follow (in some embodiments, other languages may be available).

(158) In this example, the eye examination apparatus gives verbal instructions to the subject (e.g., through a speaker) as follows:

(159) Apparatus: "We will begin a subjective test now—please listen and respond to questions."

(160) Apparatus: "Yes or no—Is the target clear to you now?" If the subject answers no, the eye examination apparatus may reperform the objective refraction measurement or select the most hyperopic objective measurement result. If the subject answers yes, the algorithm proceeds to the next step, and moves on after two additional tries.

(161) Apparatus: "You will now be presented with a choice of targets—please tell the instrument which option is better by answering with one, two, same, neither or repeat. Answer neither if neither choice of targets is clear. Answer same if both choices of targets are clear, and it is difficult to determine which is better. Answer repeat if you would like to see both choices again."

(162) FIG. **22** illustrates an example embodiment of an eye target **22000** which may be used to communicate with a subject.

(163) To further prevent the need for touch screen responses and to assist hearing impaired subjects, messages and possible subject responses can be displayed as words in the subject's preferred language or sign language, or as icons on the target screen. The eye examination apparatus may use voice recognition to determine the subject's response, or the eye examination apparatus may determine the subject's response based upon which of the provided response areas on the display the subject is fixating their eye(s) upon, and/or may interpret sign language or facial expressions to determine subject responses.

(164) As disclosed above, an eye examination apparatus comprising a multi-function ophthalmic instrument for eye health and vision examinations does not require the subject's head to be constrained during examination. It automatically and continuously aligns an internal eye measurement system to the subject's eye(s) during the measurements, regardless of normal subject motion. The optical paths for all measurements include a sufficiently large standoff to allow all measurements to take place with the subject standing comfortably distant from the housing of the

instrument, including for example a protective window separating the subject from the measurement module. The eye measurement system is capable of video rate measurements. Audio/visual cues may be provided remotely by the instrument, technician, or physician prior to, during, and after the measurement(s). By incorporating a housing with an easily disinfected smooth outer shell, and by eliminating the traditional headrest and chair, the apparatus can measure subject's eyes without the need for the subject to contact any instrument surfaces or to be in proximity to a technician or HCP during the measurements, thus greatly reducing the risks of cross contamination.

(165) While example embodiments are disclosed herein, one of ordinary skill in the art appreciates that many variations that are in accordance with the present teachings are possible and remain within the scope of the appended claims. The invention therefore is not to be restricted except within the scope of the appended claims.

Claims

1. An apparatus, comprising: an eye measurement system including an optical system, wherein the eye measurement system is configured to make at least one optical measurement of an eye of a subject; a housing having the eye measurement system disposed therein, wherein the housing includes an aperture for providing light to and from the optical system and the eye while the subject is separated and spaced apart from the housing and while the eye is not maintained in a fixed positional relationship with respect to the housing; an optical system movement arrangement which is configured to move a first optical element of the optical system; and an automatic eye tracking arrangement, wherein the automatic eye tracking arrangement is configured to ascertain a current positional relationship of the eye with respect to at least a second optical element of the optical system without human assistance, and in response thereto to control the optical system movement arrangement to move the optical system into a predetermined positional relationship with respect to the eye without human assistance, wherein the eye measurement system includes at least one measurement device, wherein the at least one measurement device is configured to make a measurement of the eye via the optical system.

2. The apparatus of claim 1, further comprising: a processing system; and a user interface, wherein the processing system is configured to interact with the subject via the user interface and in response to the interaction to adjust at least one parameter of the optical system to make the measurement of the eye.

3. The apparatus of claim 1, wherein the apparatus is configured to capture a fundus image of the eye.

4. The apparatus of claim 1, wherein the eye measurement system is configured to make a visual acuity measurement of the eye via the optical system.

5. The apparatus of claim 1, further comprising a processing system, wherein the automatic eye tracking arrangement comprises: at least one light source configured to illuminate the eye; and at least one camera configured to receive an image of the eye, wherein the camera is configured to output image data of the image of the eye to the processing system, and wherein the processing system is configured to control the optical system movement arrangement to move the optical system into the predetermined positional relationship with respect to the eye based on the image data.

6. The apparatus of claim 1, comprising an anti-microbial material disposed at an exterior surface of the housing.

7. A method, comprising: making at least one optical measurement of an eye of a subject with an apparatus; wherein the apparatus includes a housing, an eye measurement system and an automatic eye tracking arrangement, wherein the eye measurement system includes an optical system, wherein the eye measurement system is disposed within the housing, wherein the housing includes

an aperture for providing light to and from the optical system and the eye while the subject is separated and spaced apart from the housing and while the eye is not maintained in a fixed positional relationship with respect to the housing; and ascertaining, via the automatic eye tracking arrangement, without human assistance, a current positional relationship of the eye with respect to the optical system; and in response to ascertaining the current positional relationship of the eye with respect to the optical system, moving at least a first optical element of the optical system into a predetermined positional relationship with respect to the eye without human assistance, wherein making the at least one optical measurement of the eye includes capturing an external image of the eye via the optical system.

8. The method of claim 7, wherein the eye measurement system interacts with the subject via a user interface, and in response to the interaction, adjusts at least one parameter of the optical system to make the measurement of the eye.

9. The method of claim 7, comprising capturing a fundus image of the eye.

10. The method of claim 7, comprising making a visual acuity measurement of the eye via the optical system.

11. The method of claim 7, wherein ascertaining the current positional relationship of the eye with respect to the optical system comprises: illuminating the eye with at least one light source; at least one camera receiving an image of the eye; the camera outputting image data of the image of the eye to a processing system, and the processing system controlling the optical system movement arrangement to move the optical system into the predetermined positional relationship with respect to the eye based on the image data.

12. The method of claim 7, comprising the apparatus moving the optical system in three dimensions.

13. An apparatus, comprising: a housing; and an eye measurement system disposed within the housing, wherein the eye measurement system includes an element, wherein the apparatus is configured to ascertain a current positional relationship of an eye of a subject with respect to at least the element while the subject is spaced apart and separated from the apparatus, without human intervention, and wherein the eye measurement system is configured to make at least one optical measurement of the eye of the subject after the apparatus has ascertained the current positional relationship of the eye of the subject with respect to at least the element.

14. The apparatus of claim 13, wherein the apparatus is configured to capture a fundus image.

15. The apparatus of claim 13, wherein the eye measurement system includes an optical system, and wherein the optical system includes the element.

16. The apparatus of claim 15, wherein the eye measurement system is configured to make a visual acuity measurement of the eye via the optical system.

17. The apparatus of claim 15, wherein the optical system includes a first lens, and wherein the automatic eye tracking arrangement includes a Lidar device which is configured to provide light to the eye via the first lens and to receive returned light from the eye via the first lens for determining a distance between the eye and the first lens.

18. The apparatus of claim 13, further comprising: a processing system; and a user interface, wherein the processing system is configured to interact with the subject via the user interface and in response to the interaction to adjust at least one parameter of the optical system to make the measurement of the eye.

19. The apparatus of claim 13, further comprising a processing system, wherein the automatic eye tracking arrangement comprises: at least one light source configured to illuminate the eye; and at least one camera configured to receive an image of the eye, wherein the camera is configured to output image data of the image of the eye to the processing system, and wherein the processing system is configured to control the optical system movement arrangement to move the optical system into the predetermined positional relationship with respect to the eye based on the image data.

20. The apparatus of claim 13, further comprising an anti-microbial material disposed at an exterior surface of the housing.