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(54) APPARATUS, METHOD AND SYSTEM FOR MEASURING THE INFLUENCE OF OPHTHALMIC LENS DESIGN

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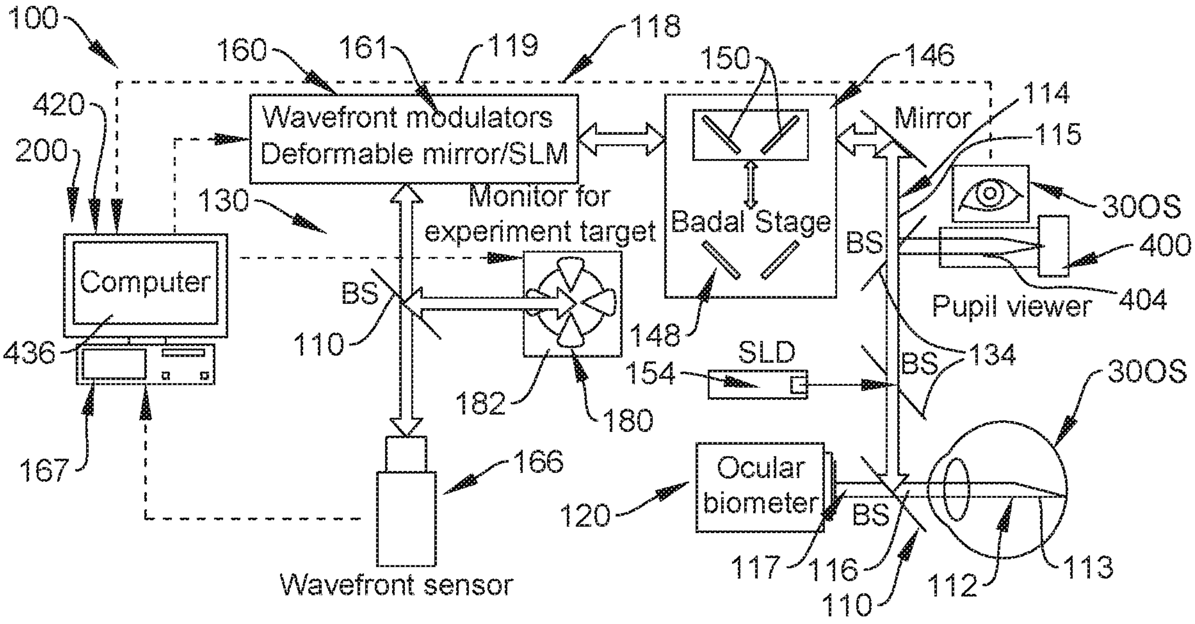
(57) ABSTRACT

A method for measuring an influence of an ophthalmic lens design is disclosed. The method comprises splitting an optical light beam into a wavefront measurement light path and a wavefront modulation light path; implementing the ophthalmic lens design in an adaptive optics device positioned in the wavefront modulation light path; and obtaining ocular biometric data in the ocular biometric and wavefront measurement light path to measure the influence of the ophthalmic lens design. Also disclosed are an apparatus and a system for measuring an influence of an ophthalmic lens design along with a method for assembling the device and system. The ocular biometric device may be an interferometer and the adaptive optics device may comprise one or more wavefront shapers.



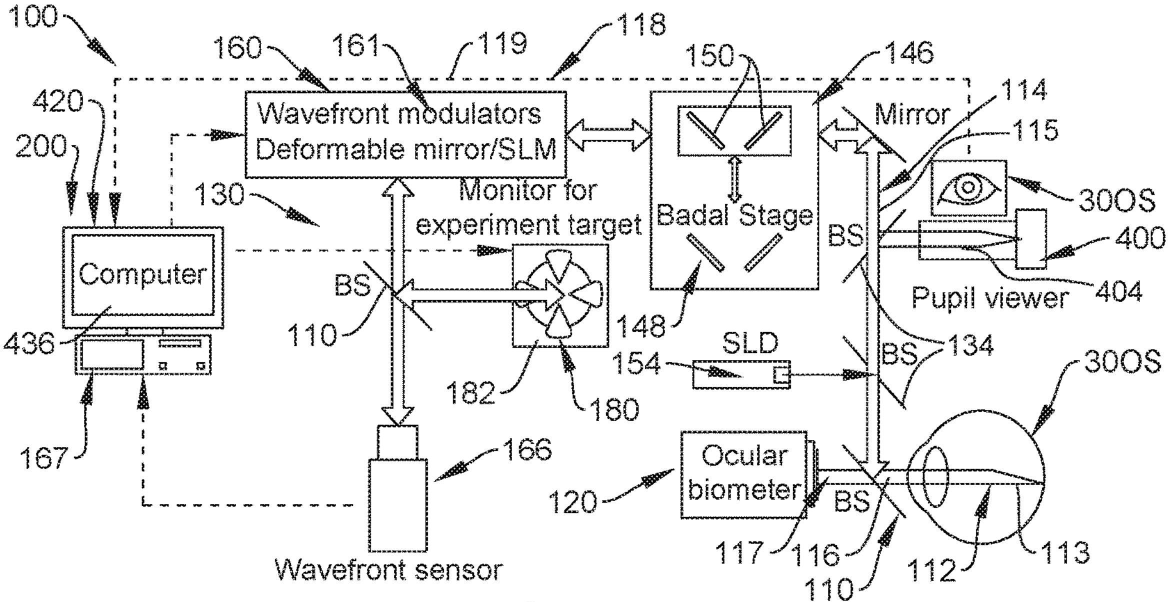

100
160
161
119
118
150
146
420
200
Wavefront modulators
Deformable mirror/SLM
Mirror
114
115
130
Monitor for
experiment target
Badal Stage
30OS
BS
400
Computer
BS
404
Pupil viewer
436
110
148
BS
134
SLD
154
30OS
182
180
167
166
Ocular
biometer
120
BS
Wavefront sensor
117
116
112
113
110

FIG. 1A

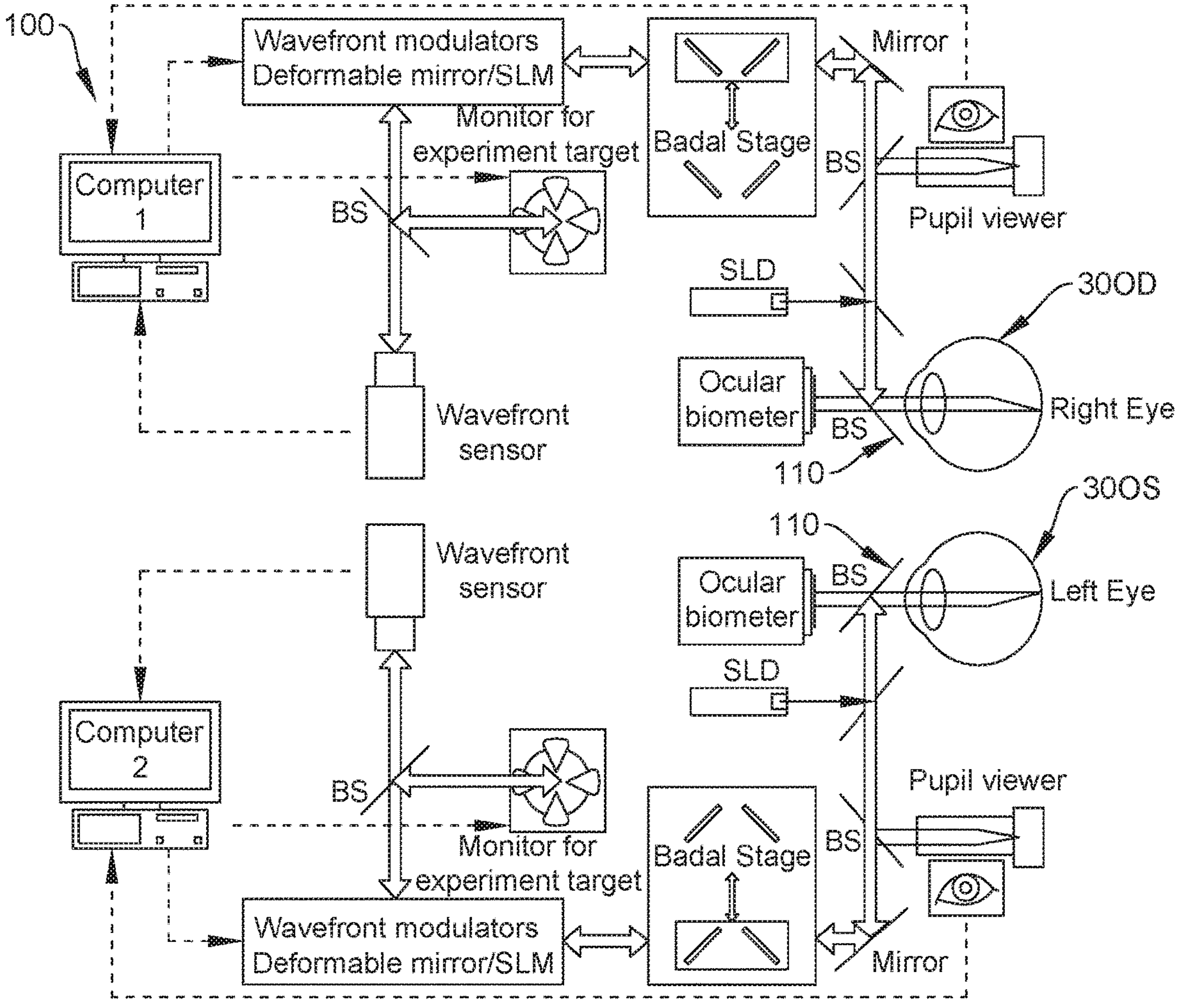

100
Wavefront modulators
Deformable mirror/SLM
Mirror
Monitor for
experiment target
Badal Stage
Computer
1
BS
BS
Pupil viewer
SLD
30OD
Wavefront
sensor
Ocular
biometer
Right Eye
BS
110
30OS
110
Wavefront
sensor
BS
Ocular
biometer
Left Eye
SLD
Computer
2
Pupil viewer
BS
BS
Monitor for
experiment target
Badal Stage
Wavefront modulators
Deformable mirror/SLM
Mirror

FIG. 1B

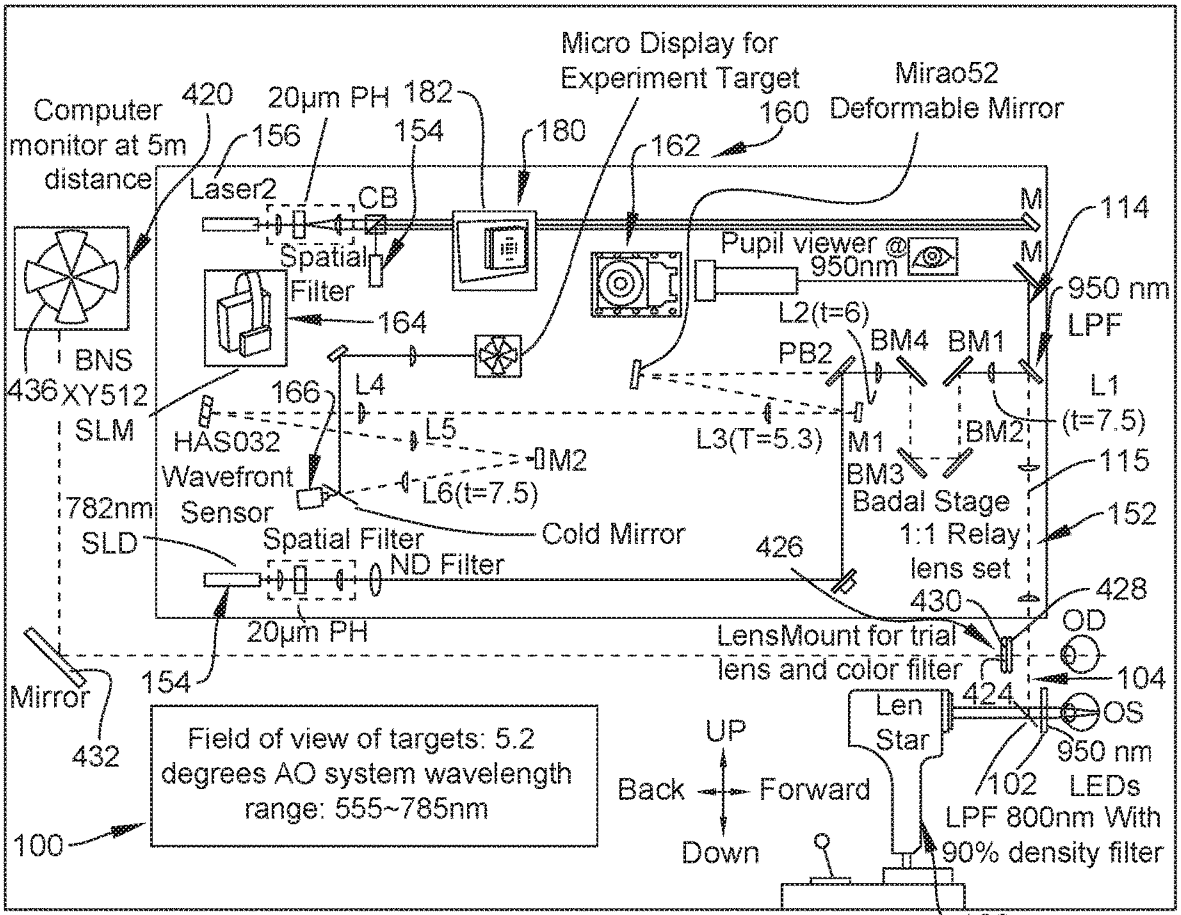
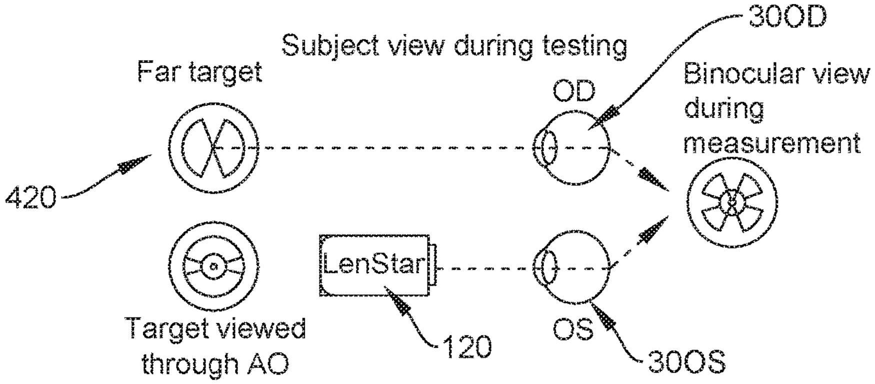


FIG. 1C



Far target (Vertical limb of cross) in right eye (OD) controls accommodation
Adaptive optic blurs (horizontal limb of cross) in left (OS - tested) eye
Outer ring provides fusion lock (controls binocular fusion)
Lenstar target (red dot) is aligned/superimposed at center of cross for foveal axial length
Subject is instructed to keep the vertical limb of the cross in focus at all times

FIG. 1D

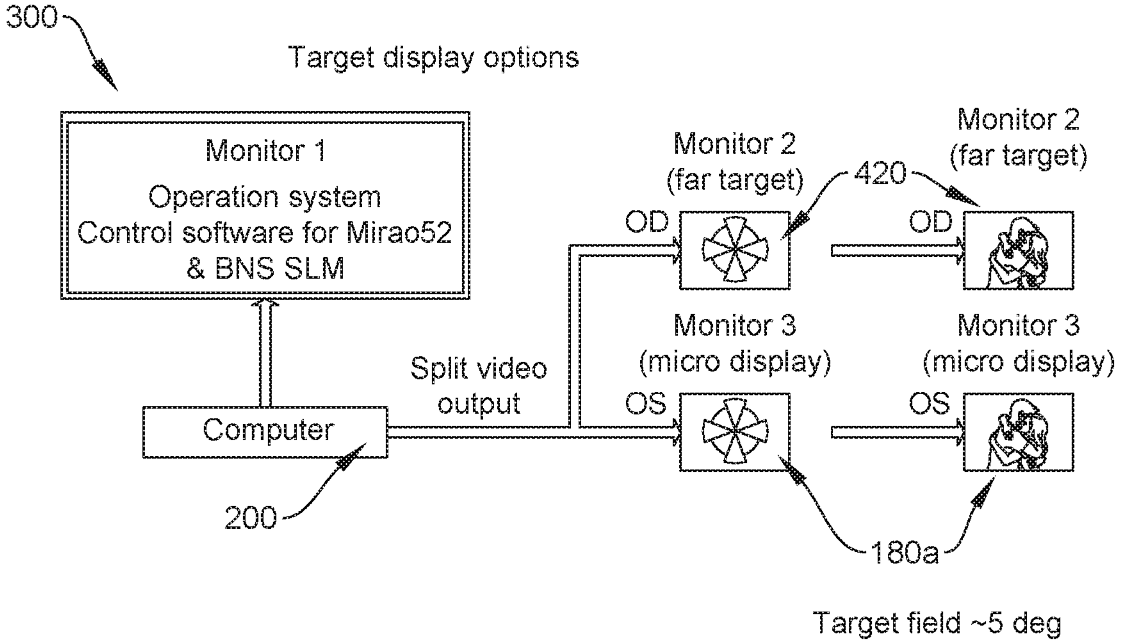

300
Target display options
Monitor 1
Operation system
Control software for Mirao52
& BNS SLM
Computer
200
Split video
output
Monitor 2
(far target)
OD
420
Monitor 2
(far target)
OD
Monitor 3
(micro display)
OS
Monitor 3
(micro display)
OS
180a
Target field ~5 deg

FIG. 1E

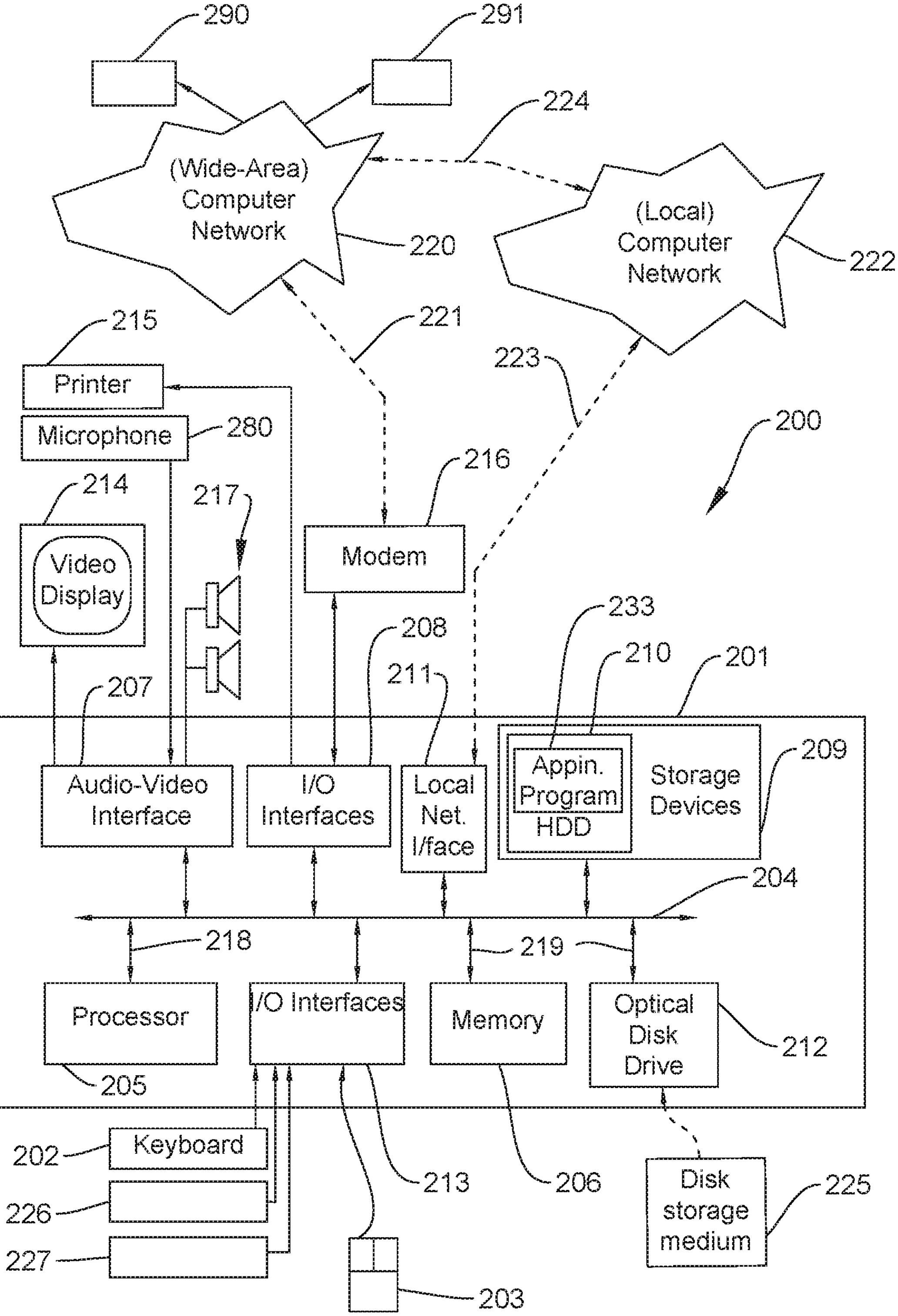

290
291
224
(Wide-Area) Computer Network
220
(Local) Computer Network
222
221
223
215
Printer
Microphone
280
200
216
214
217
Video Display
Modem
233
208
210
201
211
207
209
Audio-Video Interface
I/O Interfaces
Local Net. I/face
Appln. Program
HDD
Storage Devices
204
218
219
Processor
I/O Interfaces
Memory
Optical Disk Drive
212
205
202
Keyboard
213
206
Disk storage medium
225
226
227
203

FIG. 2A

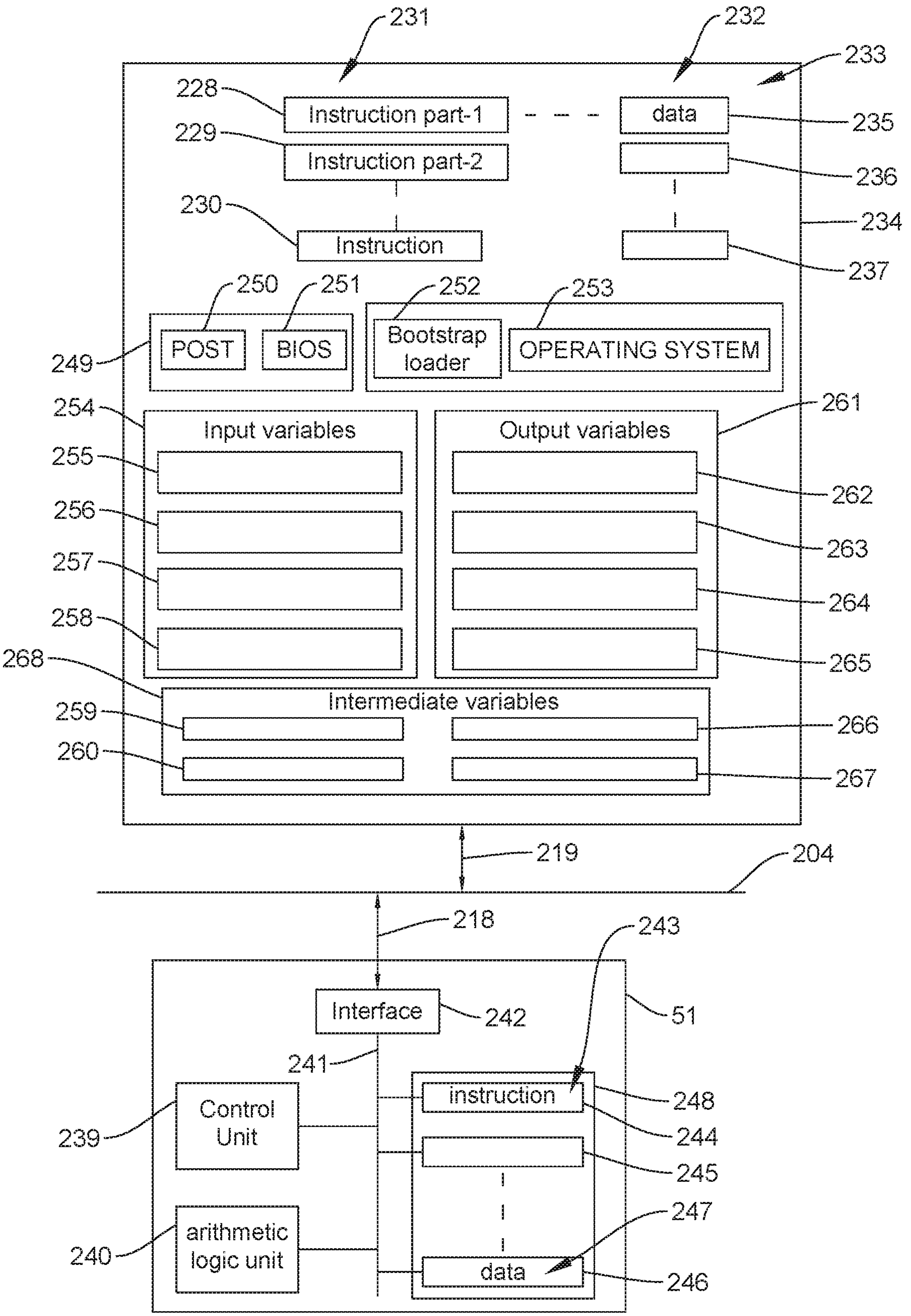

231
232
233
228
Instruction part-1
data
235
229
Instruction part-2
236
230
Instruction
234
237
250
251
252
253
POST
BIOS
Bootstrap loader
OPERATING SYSTEM
249
254
Input variables
Output variables
261
255
256
257
258
262
263
264
265
268
Intermediate variables
259
260
266
267
219
204
218
243
Interface
242
51
241
Control Unit
239
instruction
248
244
245
247
arithmetic logic unit
240
data
246

FIG. 2B

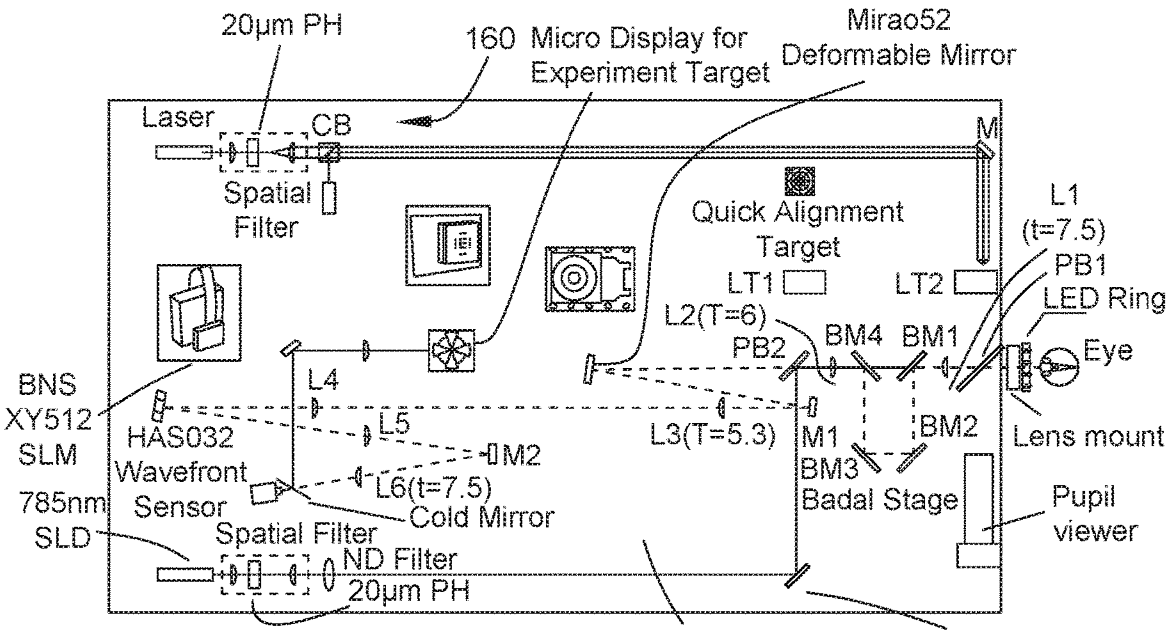


FIG. 3A

Field of view of targets: 5.2 degrees AO system wavelength range: 555~785 nm

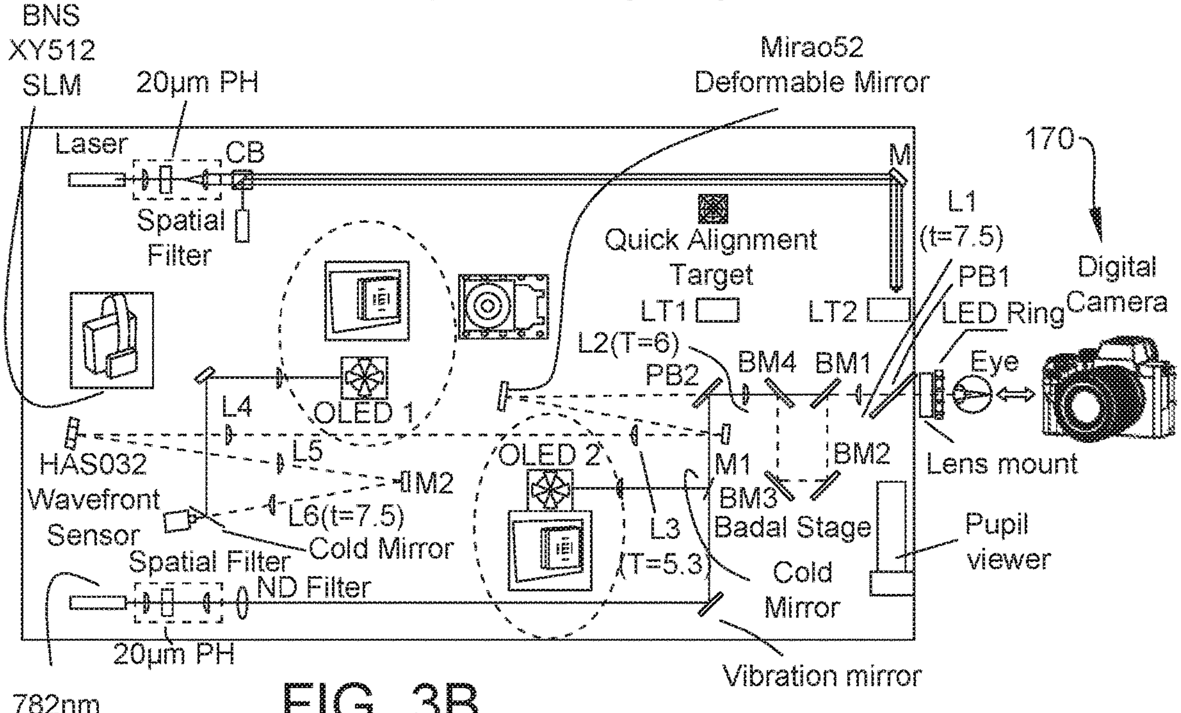


FIG. 3B

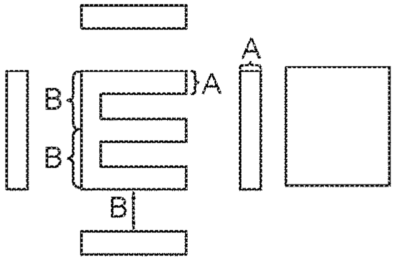


FIG. 3C

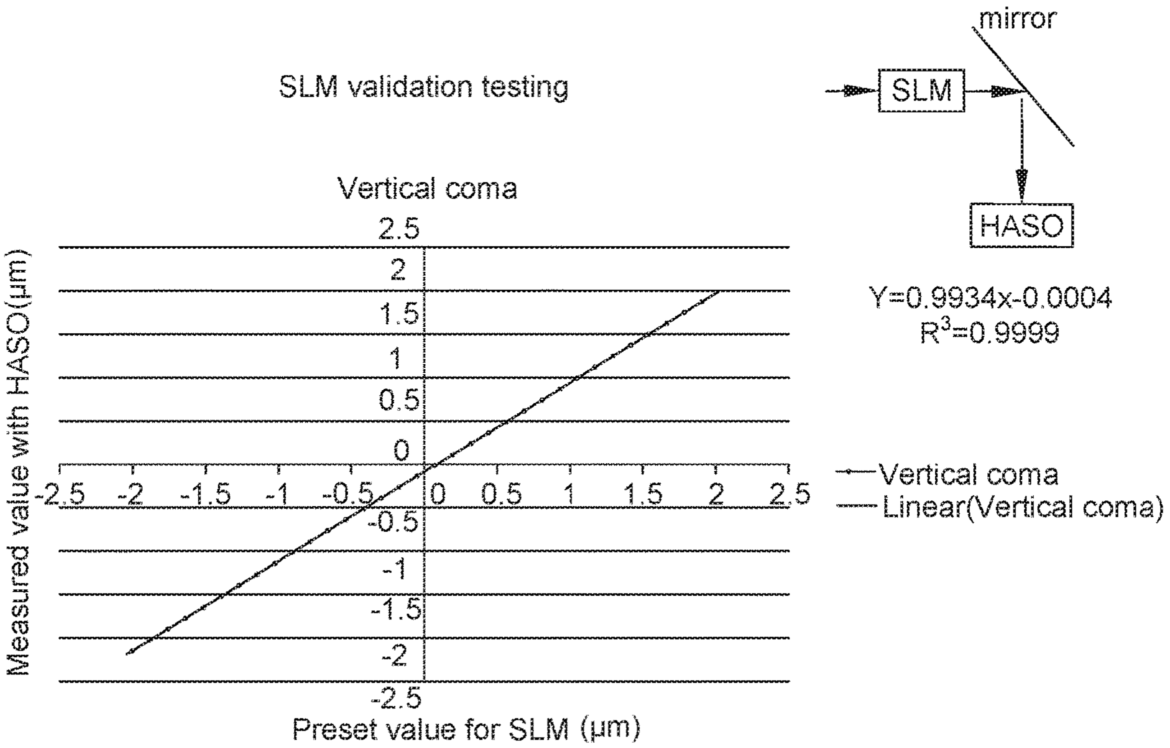

SLM validation testing
mirror
SLM
HASO
Vertical coma
Y=0.9934x-0.0004
R3=0.9999
2.5
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
-2.5 -2 -1.5 -1 -0.5 0 0.5 1 1.5 2 2.5
Measured value with HASO(μm)
Preset value for SLM (μm)
Vertical coma
Linear(Vertical coma)

FIG. 4A

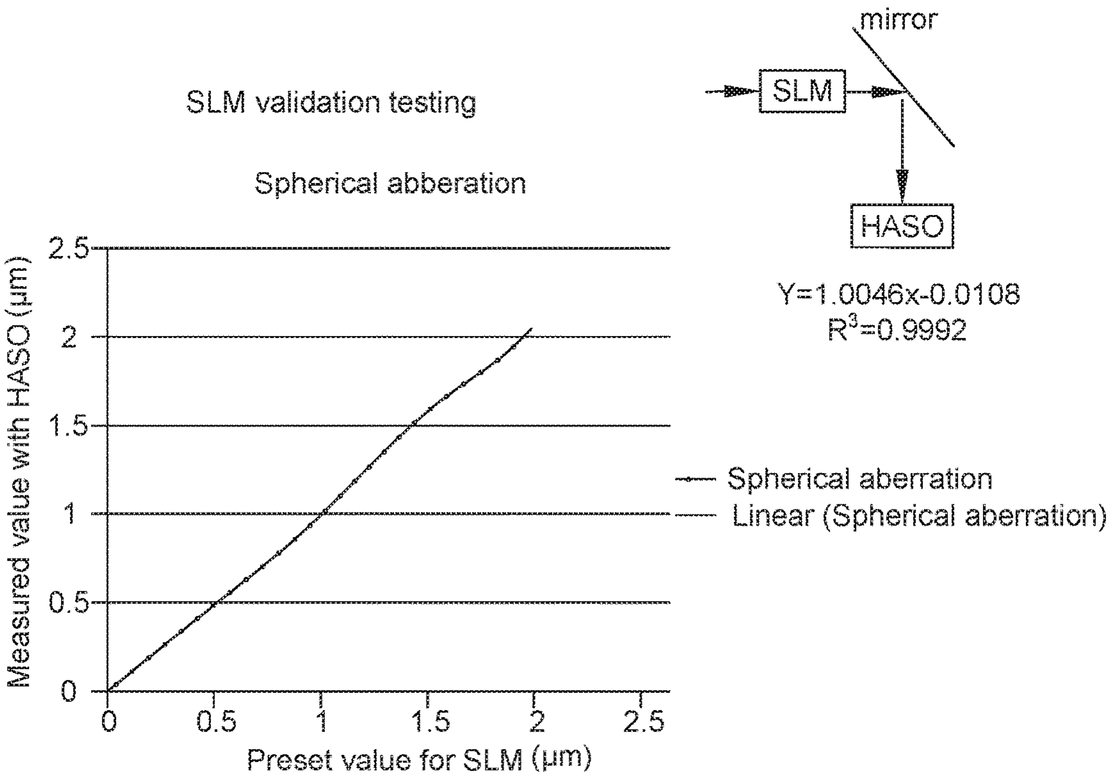

SLM validation testing
mirror
SLM
HASO
Spherical abberation
Y=1.0046x-0.0108
R3=0.9992
2.5
2
1.5
1
0.5
0
0 0.5 1 1.5 2 2.5
Measured value with HASO (μm)
Preset value for SLM (μm)
Spherical aberration
Linear (Spherical aberration)

FIG. 4B

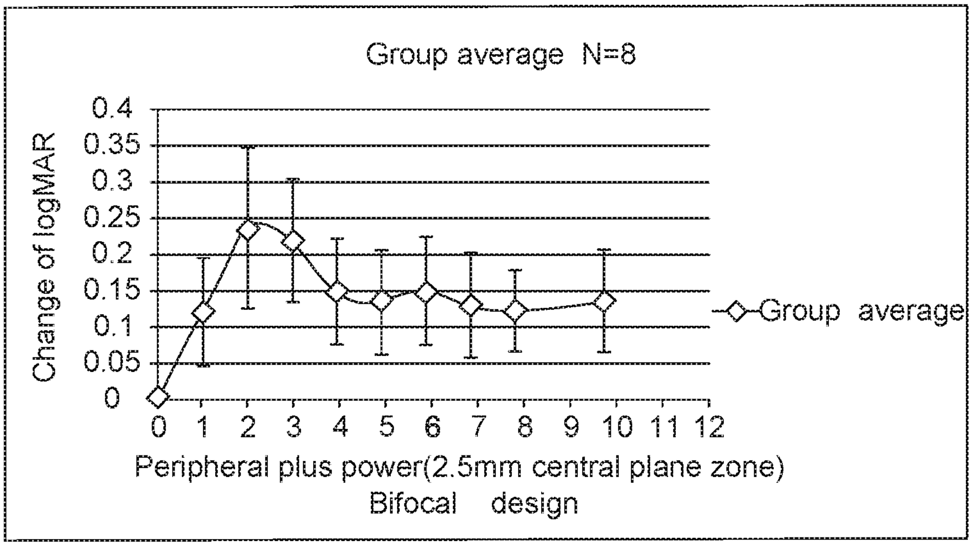

Group average N=8
Change of logMAR
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0 1 2 3 4 5 6 7 8 9 10 11 12
Peripheral plus power(2.5mm central plane zone)
Bifocal design
Group average

FIG. 5

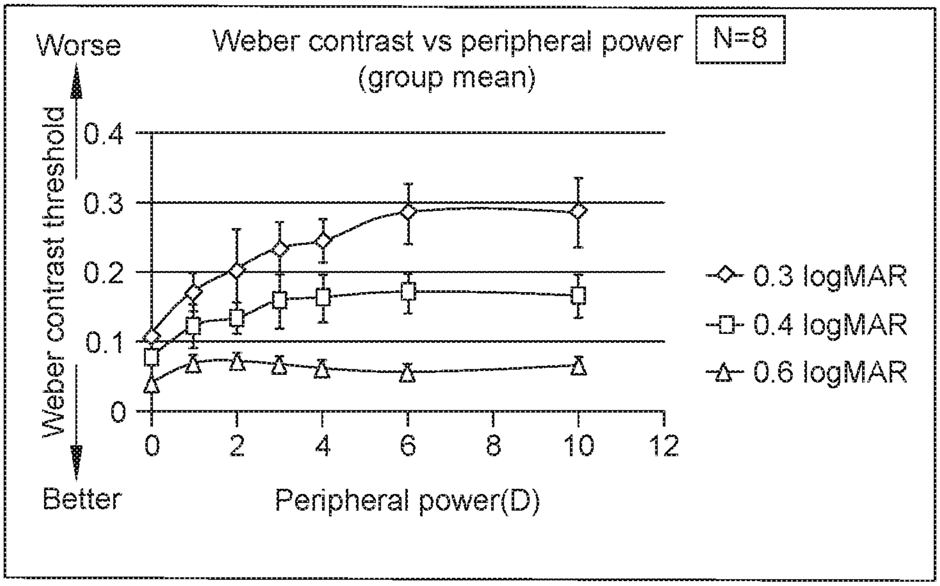

Worse
Weber contrast vs peripheral power
(group mean)
N=8
Weber contrast threshold
0.4
0.3
0.2
0.1
0
0 2 4 6 8 10 12
Better
Peripheral power(D)
0.3 logMAR
0.4 logMAR
0.6 logMAR

FIG. 6

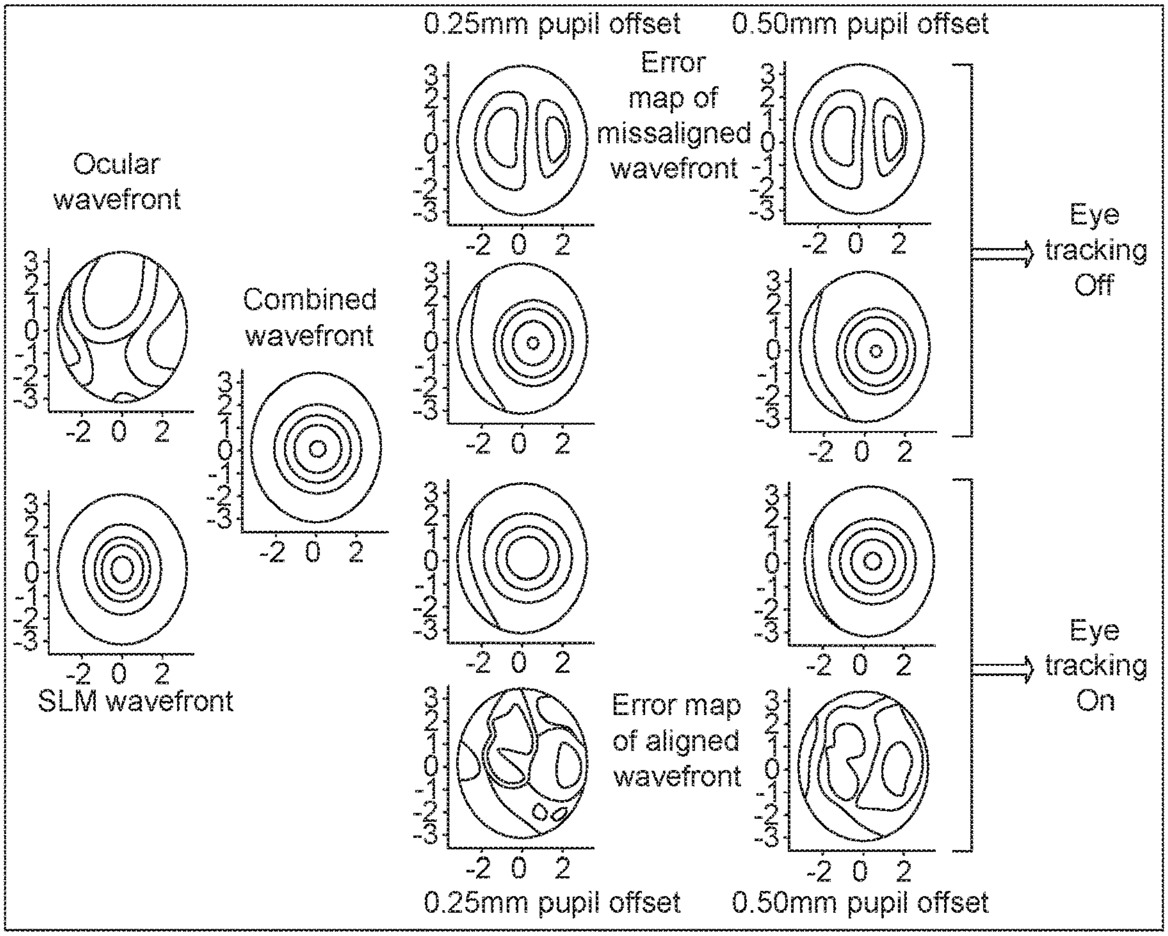

0.25mm pupil offset
0.50mm pupil offset
Error map of missaligned wavefront
Ocular wavefront
Combined wavefront
Eye tracking Off
Eye tracking On
SLM wavefront
Error map of aligned wavefront
0.25mm pupil offset
0.50mm pupil offset
3 2 1 0 -1 -2 -3
-2 0 2

FIG. 7

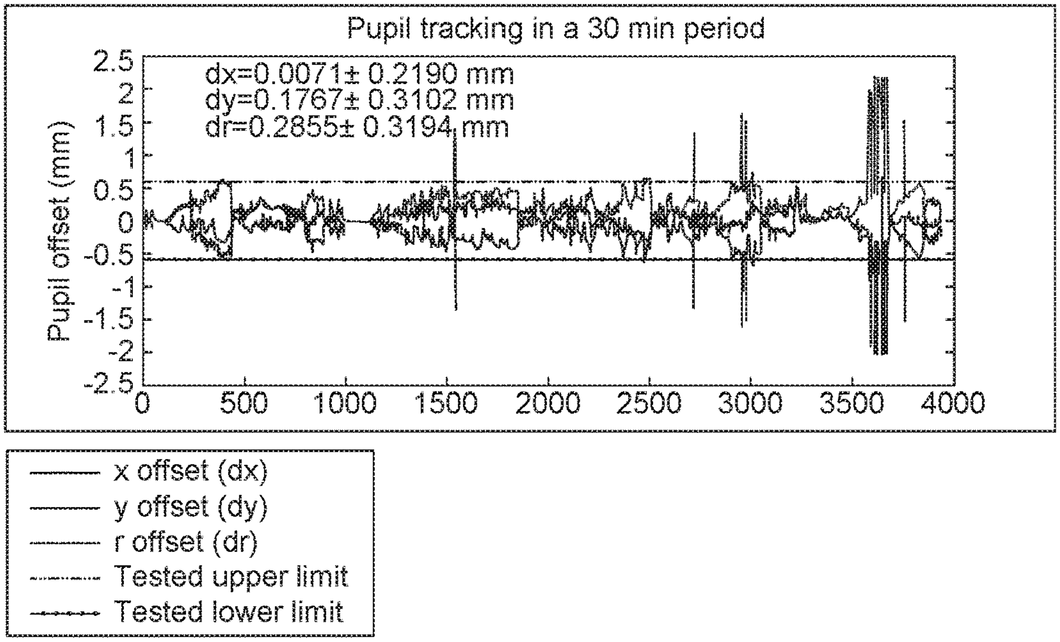

Pupil tracking in a 30 min period
dx=0.0071± 0.2190 mm
dy=0.1767± 0.3102 mm
dr=0.2855± 0.3194 mm
Pupil offset (mm)
2.5
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
0
500
1000
1500
2000
2500
3000
3500
4000
x offset (dx)
y offset (dy)
r offset (dr)
Tested upper limit
Tested lower limit

FIG. 8

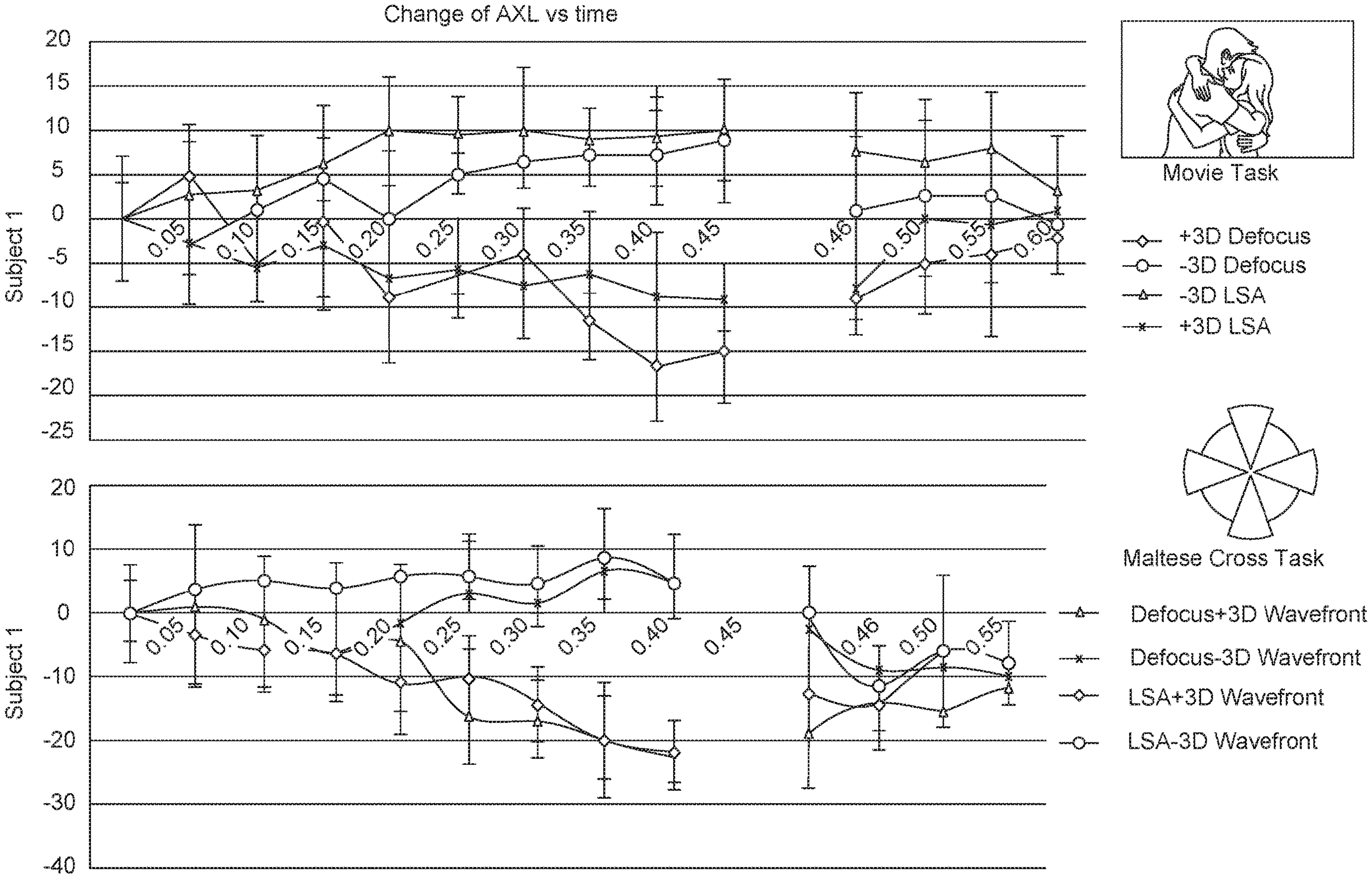

Change of AXL vs time
Subject 1
20
15
10
5
0
-5
-10
-15
-20
-25
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
0.45
0.46
0.50
0.55
0.60
Movie Task
+3D Defocus
-3D Defocus
-3D LSA
+3D LSA
Subject 1
20
10
0
-10
-20
-30
-40
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
0.45
0.46
0.50
0.55
Maltese Cross Task
Defocus+3D Wavefront
Defocus-3D Wavefront
LSA+3D Wavefront
LSA-3D Wavefront

FIG. 9

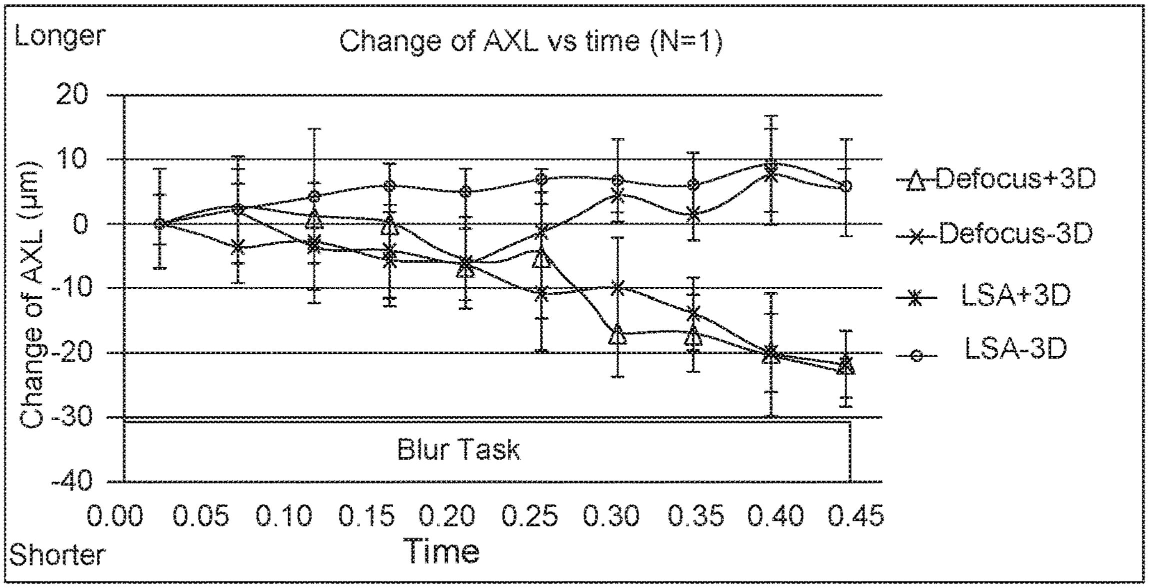


FIG. 10

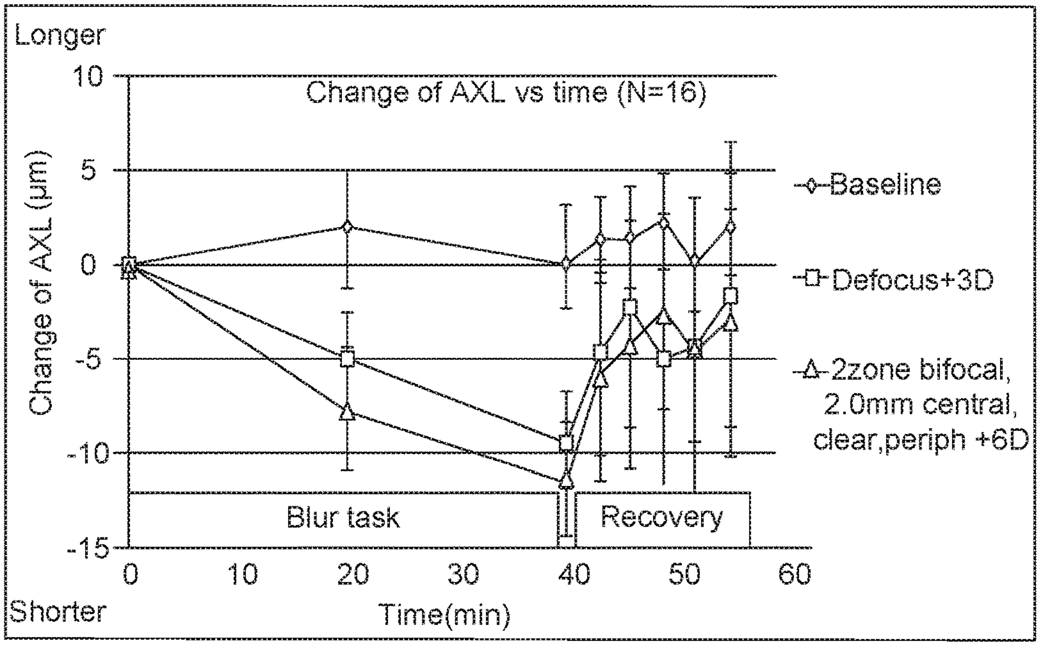


FIG. 11

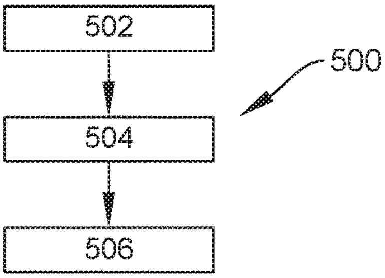


FIG. 12

APPARATUS, METHOD AND SYSTEM FOR MEASURING THE INFLUENCE OF OPHTHALMIC LENS DESIGN

FIELD OF THE INVENTION

[0001] The present invention relates to an apparatus, method and system for implementing and measuring the influence of ophthalmic lens designs. More particularly, this invention relates to an apparatus, method and system comprising an adaptive optics device and an optical biometric device.

BACKGROUND TO THE INVENTION

[0002] The correction of myopia by eye care practitioners has traditionally involved the use of lenses to bring light into sharp focus on the retina, thereby improving the quality of vision. This approach provides clear vision for the myopic patient, but does not slow or stop the progression of myopia. It is now evident that the growth of the human eye and the progression of myopia can be influenced by the optical characteristics of the retinal image.

[0003] The eyes of all animal species researched to date, show the capacity to detect the sign (direction) of defocus of light at the retina and to respond to it by growing towards the optimal focus. Hyperopic (negative) blur causes the eye to grow longer and myopic (positive) blur causes the eye to stop growing and in some cases to slightly shorten. This process of the eye growing to a length that focuses the image of light at the retinal plane is referred to as emmetropization, where the eye is growing to attain emmetropia and clear vision. Myopia (and hyperopia) arises when this emmetropization process fails to provide a close match between the axial length and the optical power of the eye to produce a clear retinal image and the eye grows too long for the image plane. In young children, the eye naturally grows longer and the optical power of the eye reduces so that by about the start of puberty, the eye has reached adult length and is emmetropic. However in myopic children, the eye grows rapidly and continues to grow during the teenage years.

[0004] What causes the myopic child's eye to continue to grow is not yet established. It reflects an apparent failure of the emmetropization process. Various theories have been proposed as to what might lead to a hyperopic cue for eye growth in the myopic child's eye. On the other hand, the introduction of myopic defocus into the retinal image of the myopic child's eye, has been proposed as a logical method to slow or stop excessive eye growth. While myopic defocus can slow eye growth, it also degrades vision.

[0005] Prospective clinical trials have shown that the rate of myopia progression in humans can be influenced by the optical design of soft contact lenses. These clinical trials have established that the introduction of positive defocus in the retinal image of children slows the progression of myopia. Changes in eye length associated with defocus are modulated by changes in both scleral growth and choroidal thickness, the net effect of which results in an anterior or a posterior movement of the retina toward the image plane. Induced myopic defocus, leads to a thickening of the choroid and to a decreased scleral growth rate (which results in anterior movement of the retina), and induced hyperopic defocus leads to a thinning of the choroid and an increase in scleral growth rate (which results in posterior movement of the retina). Choroidal thickness changes in response to imposed defocus have been observed in both avian and primate animal models, and have been demonstrated to occur rapidly and to precede longer term, sclera-mediated changes in eye size.

[0006] The introduction of precise methods for measuring eye dimensions has led to the finding that a number of factors can lead to short-term changes in optical axial length (the axial distance from the anterior cornea to the retinal pigment epithelium) of human subjects. Changes in accommodation and intra-ocular pressure have both been found to be associated with short-term changes in axial length and small but significant diurnal variations have also been noted to occur in human axial length, which are primarily mediated by changes in choroidal thickness.

[0007] Research has shown that in young adult human subjects, short-term changes in the choroid thickness and axial length occur in a way similar to that observed in other animal species in response to optical defocus. Studies investigating the time course of choroidal thickness changes in response to defocus, have illustrated that these changes occur within minutes of exposure. When the defocus is imposed for a day, it significantly disrupts the normal diurnal rhythms in choroidal thickness and axial length with predictable patterns of change depending on the sign of the defocus.

[0008] Optical designs for the control of myopia progression are currently based on the principle of incorporating positive power to focus light in front of the retina, while at the same time focusing some light on the retina to provide distance vision correction. This optical constraint leads to some loss of visual performance.

[0009] The presence of positive power in the retinal image therefore creates two competing outcomes, myopia control versus vision quality. Improved mechanisms of understanding how these competing factors interact are desired to optimize the optical design of lenses.

[0010] The reference to any prior art in this specification is not, and should not be taken as, an acknowledgement or any form of suggestion that the prior art forms part of the common general knowledge.

OBJECT OF THE INVENTION

[0011] It is a preferred object of the embodiments of the present invention to provide an apparatus that addresses or at least ameliorates one or more of the aforementioned problems of the prior art and/or provides a useful commercial alternative.

SUMMARY OF THE INVENTION

[0012] Generally, embodiments of the present invention relate to an apparatus, method and system for implementing and measuring the influence of an ophthalmic lens design.

[0013] In a broad form the invention relates to an apparatus, method and system comprising an adaptive optics device to implement an ophthalmic lens design. The influence of the ophthalmic lens design can be then be measured with an optical biometric device.

[0014] In a first form, although it need not be the only or indeed the broadest form, the invention provides a method for measuring an influence of an ophthalmic lens design comprising:

- **[0015]** splitting an optical light beam into a wavefront measurement light path and a wavefront modulation light path;
- **[0016]** implementing the ophthalmic lens design in an adaptive optics device positioned in the wavefront modulation light path; and
- **[0017]** obtaining ocular biometric data in the ocular biometric measurement light path to measure the influence of the ophthalmic lens design.

[0018] In a second form, the invention provides an apparatus for measuring an influence of an ophthalmic lens design comprising:

- **[0019]** a beam splitter which splits an optical light path into a wavefront measurement light path and a wavefront modulation light path;
- **[0020]** an adaptive optics device positioned in the wavefront modulation light path to implement the ophthalmic lens design; and
- **[0021]** an ocular biometric device positioned in the ocular biometric measurement light path to obtain ocular biometric data.

[0022] In a third form, the invention provides a system for measuring an influence of an ophthalmic lens design comprising:

- **[0023]** a beam splitter for splitting an optical light path into a wavefront modulation light path and a wavefront measurement light path;
- **[0024]** an adaptive optics device positioned in the wavefront modulation light path; one or more processor for controlling the adaptive optics device to implement the ophthalmic lens design; and
- **[0025]** an ocular biometric device positioned in the ocular biometric measurement light path for obtaining ocular biometric data.

[0026] In a fourth form, the invention provides a method for assembling the device of the second form or the system of the third form, the method comprising:

- **[0027]** installing a beam splitter to split an optical light path into a wavefront measurement light path and a wavefront modulation light path;
- **[0028]** positioning an adaptive optics device in the wavefront modulation light path to implement the ophthalmic lens design;
- **[0029]** when directed to a system, connecting one or more processor to control the adaptive optics device to implement the ophthalmic lens design; and
- **[0030]** positioning an ocular biometric device in the ocular biometric measurement light path to obtain ocular biometric data.

[0031] In a fifth form, the invention provides an ophthalmic lens comprising the ophthalmic lens design implemented in the first form or the third form.

[0032] The ophthalmic lens of the fifth form may comprise a contact lens.

[0033] In a sixth form, the invention provides a method for optimising a lens design using the method of the first form, the apparatus of the second form or the system of the third form.

[0034] In a seventh form, the invention provides an ophthalmic lens comprising the optimised lens design of the sixth form.

[0035] According to any above form, the beam splitter may comprise any suitable device for splitting a light beam into two or more beams. The beam splitter may comprise a pellicle beam splitter, a cube beamsplitter, a dichroic mirror, a band filter or a longpass/shortpass filter.

[0036] According to any above form, the biometric device comprises a non-contact ocular biometric device. The ocular biometric device may comprise an interferometer. The interferometer may comprise a laser interferometer or a low coherence interferometer. The interferometer may comprise an optical biometer or an optical coherence tomographer (OCT).

[0037] According to any above form, the adaptive optics device comprises one or more wavefront shapers. The one or more wavefront shapers may comprise one or more spatial light modulator and/or one or more adaptive minor.

[0038] According to any above form, the spatial light modulator may be comprised of a liquid crystal layer that changes refractive index for optical modulation, in response to an array of underlying electrodes. The spatial light modulator may comprise square liquid crystal cells with a pixel or optical element size of 15×15 microns. The spatial light modulator may comprise a square 7.68×7.68 mm active area.

[0039] According to any above form, the spatial light modulator may be operated by a controller to adjust the shape of a generated wavefront.

[0040] According to any above form, the adaptive mirror may be driven by one or more actuators to adjust the shape of a generated wavefront.

[0041] According to any above form, the one or more wavefront shapers may comprise one or more spatial light modulators and/or adaptive minors in combination.

[0042] According to any above form, the adaptive optics device may further comprise a wavefront sensor.

[0043] According to any above form, the adaptive optics device may further comprise a plurality of optical elements. The plurality of optical elements may comprise a focus corrector. The focus corrector may comprise a Badal stage. The Badal stage may comprise two or more Badal stage mirrors. The plurality of optical elements may further comprise one or more relay lens set; one or more mirrors; one or more lenses; one or more beam splitters; and/or one or more cold minors.

[0044] According to any above form, the adaptive optics device may further comprise one or more micro-display. The one or more micro-display may comprise a primary micro-display and a secondary micro-display. The primary micro-display may be viewable through the two or more wavefront shapers. Each of the one or more micro-display may comprise any suitable display such as, an LED or OLED display.

[0045] Each of the one or more micro-displays may be individually or collectively synchronised to display vision tests including visual acuity and contrast sensitivity.

[0046] Each of the one or more micro-displays may also be individually or collectively synchronised to display a movie or collection of images of the viewer's choice.

[0047] According to any above form, each of the one or more micro-display may comprise a fine reference scale and/or a grayscale. The grayscale may comprise 256 levels.

[0048] According to any above form, the secondary micro-display may be aligned so that the image displayed thereon overlays with an image displayed on the primary micro-display. The images displayed on the secondary micro-display may be under independent optical control.

[0049] According to any above form, an image displayed on a micro-display may be manipulated with imposition of an optical design while the image displayed on the secondary display may be used as a reference.

[0050] According to any above form, the optical elements may comprise an objective lens in front of the secondary micro-display to produce the same through-system magnification as in the primary micro-display.

[0051] According to any above form, the adaptive optics device may further comprise an imaging device, such as a digital camera with its image plane conjugate to or replacing the retinal plane of the eye.

[0052] According to any above form, the method, apparatus, and system may further comprise an illumination source. The illumination source may comprise one or more LED. The one or more LED may be arranged in a ring.

[0053] According to any above form, the method, apparatus, and system may further comprise a lens mount and a lens positioned before the beam splitter.

[0054] According to any above form, the method, apparatus, and system may further comprise a pupil tracker system. A pupil viewer, such as a digital camera, may be positioned in a pupil tracking path. The pupil tracking path may comprise a pupil tracking beam splitter. The pupil tracking system may comprise a pupil tracker illumination source. The pupil tracker illumination source may illuminate at a near infrared wavelength. The near infrared wavelength may comprise 700 to 2500 nm; 800 to 1100 nm; or 900 to 1000 nm. In one embodiment the near infrared wavelength comprises 950 nm.

[0055] The apparatus and system may further comprise one or more superluminescent diode to create a point source of light at the retina for wavefront measurement.

[0056] The apparatus and system may further comprise a superluminescent diode for alignment

[0057] According to any above form, the method, apparatus, and system may further comprise a fellow eye **30**OD display. The fellow eye display may be synchronised with a respective one or more micro-display.

[0058] According to any above form, the method, apparatus, and system may further comprise fellow eye optical elements. The fellow eye optical elements may comprise one or more of a lens and a colour filter. The fellow eye optical components, or a portion thereof, may be comprised in a fellow eye lens mount. The fellow eye optical elements may comprise a mirror between the fellow eye lens mount and the fellow eye display.

[0059] According to any above form, the method, apparatus and system may comprise a binocular method, apparatus and system comprising splitting, implementing and obtaining for both eyes. The binocular system also comprises controlling the adaptive optics device for both eyes.

[0060] The biometric data obtained may comprise one or more of: choroidal thickness; optical axial length (distance from the anterior corneal surface to the retinal pigment epithelium); vitreous chamber depth; anterior chamber depth; crystalline lens thickness; corneal thickness; retinal thickness (or layers within the retina); and scleral thickness. These biometric data may be acquired along any axis of the eye, but will typically be acquired along the visual axis as the person being tested views the biometer's fixation target.

[0061] Further aspects and/or features of the present invention will become apparent from the following detailed description.

BRIEF DESCRIPTION OF THE DRAWINGS

[0062] In order that the invention may be readily understood and put into practical effect, reference will now be made to embodiments of the present invention with reference to the accompanying drawings, wherein like reference numbers refer to identical elements. The drawings are provided by way of example only, wherein:

[0063] FIG. **1**A is a schematic diagram showing one embodiment of an apparatus according to the invention.

[0064] FIG. **1**B is a schematic diagram illustrating a binocular apparatus according to one embodiment of the invention.

[0065] FIG. **1**C is a schematic diagram illustrating another embodiment of an apparatus according to the invention.

[0066] FIG. **1**D is a schematic diagram illustrating the subject view according to one embodiment of the invention.

[0067] FIG. **1**E is a schematic diagram showing one embodiment of the system according to the invention.

[0068] FIG. **2**A is a schematic diagram showing one embodiment of a computing device suitable for use according to one embodiment of the invention;

[0069] FIG. **2**B is a schematic diagram showing one embodiment of a processor and memory suitable for use according to one embodiment of the invention.

[0070] FIG. **3**A is a schematic diagram showing one embodiment of an adaptive optics device according to the invention.

[0071] FIG. **3**B is a schematic diagram showing another embodiment of an adaptive optics device according to the invention.

[0072] FIG. **3**C shows a visual target for visual acuity testing according to one embodiment of the invention.

[0073] FIGS. **4**A and **4**B are line graphs showing validation testing of the SLM.

[0074] FIG. **5** shows the effect of increasing the amplitude of plus power in the peripheral zone of a centre clear bifocal design on the subject's visual acuity.

[0075] FIG. **6** shows the contrast sensitivity of three letter sizes 0.3, 0.4 and 0.6 logMAR, affected by increasing peripheral power in a centre clear bifocal design.

[0076] FIG. **7** is a graphic illustration showing the effect of pupil tracking on the combined wavefront. The combined wavefront of a model eye and predetermined wavefront pattern was measured with and without pupil tracking. Two horizontal pupil offset conditions were tested (dx=0.25 and 0.5 mm). Significantly larger amount of residual wavefront error was found in non-tracked measurements.

[0077] FIG. **8** is a graph showing pupil tracking in a subject's eye. The pupil tracking was over 30 minutes. The subject's head was positioned on a chinrest without the use of a bite bar. The subject tried to stay as still as possible for the full 30 minutes. During the measurement, the subject blinked normally. The subject was allowed to close his eyes for 10 seconds after every 1 minute of measurement. The sampling frequency was about 4 Hz (some blinks missed due to sampling frequency).

[0078] FIG. **9** is a graphic showing the change of axial length using the movie task (top) and the Maltese cross task (bottom).

[0079] FIG. **10** shows a subject's axial length change during a 40 min blur task of viewing through different optical designs, including +3D defocus, −3D defocus, +3D longitudinal spherical aberration and −3D longitudinal spherical aberration.

[0080] FIG. **11** shows the average changes (N=16) of axial length during a 40 min blur task and a 20 min recovery period after viewing through different optical designs, including baseline, +3D defocus and a 2 zone bifocal with a 2.0 mm central clear and periph +6 D.

[0081] FIG. **12** is a flowchart showing the method according to one embodiment of the invention.

[0082] Skilled addressees will appreciate that elements in the drawings are illustrated for simplicity and clarity and have not necessarily been drawn to scale. For example, the relative dimensions of some elements in the drawings may be distorted to help improve understanding of embodiments of the present invention.

DETAILED DESCRIPTION OF THE INVENTION

[0083] Embodiments of the present invention relate to an apparatus, method and system for implementing an ophthalmic lens design. Once implemented, the influence of the ophthalmic lens design can then be measured with an optical biometric device.

[0084] In one embodiment, the invention relates to a method, apparatus and system comprising an adaptive optics device and an optical biometric device for measuring the influence of ophthalmic lens design.

[0085] "Ophthalmic lens" as used herein refers to any lens for an eye or for wearing in front of an eye. The ophthalmic lens may be a corrective lens. The ophthalmic lens may be for treating myopia, hyperopia, astigmatism, presbyopia or any ophthalmic disease or condition. The ophthalmic lens may comprise glasses or spectacle lens/lenses, a contact lens, an intraocular lens or any form of ophthalmic lens.

[0086] As used herein a "wavefront shaper" is any adaptive optics device that can modify a wavefront. In the present invention, the wavefront shapers are used to modify a wavefront to implement an ophthalmic lens design by putting that ophthalmic lens design into effect.

[0087] Some of the important aspects of vision that the inventors anticipate to be impacted by the myopia control designs are visual acuity and contrast sensitivity. Therefore the inventors have placed importance on investigating these aspects of vision.

[0088] To quantify the visual performance with ophthalmic lens designs, the inventors have provided an adaptive optics apparatus **100** (see FIG. **1**A) comprising a viewing channel, so that aspects of vision performance can be measured while the subject views the image or screen target **184** displayed on screen **182** through the optical designs **10** implemented in the adaptive optics device **160**.

[0089] The embodiment of apparatus **100** for measuring an influence of an ophthalmic lens design shown in FIG. **1**A, comprises a beam splitter **110** for splitting the optical light path **112** associated with an eye to be measured **30**OS into an adaptive optics light path **114** and a measurement light path **116**. While, FIG. **1**A shows measurement of the left eye, OS, either the right eye OD or the left eye OS may be the measured eye with the other eye being the fellow eye.

[0090] An adaptive optics device **160** is positioned in the adaptive optics light path **114** to receive the optical light path beam **115** and to implement the ophthalmic lens design.

[0091] An ocular biometric device **120** is positioned in the ocular biometric measurement light path **116** to obtain biometric data from eye **30**OS.

[0092] FIG. **1**A shows one embodiment of an adaptive optics device **100** according to the invention. FIG. **1**B shows one embodiment of a binocular embodiment of an adaptive optics device **100** according to the invention. FIG. **1**C shows another embodiment of an adaptive optics device **100** according to the invention that was used to perform the experiments detailed below.

[0093] The beam splitter **110** may comprise any suitable device for splitting a light beam into two or more beams. The beam splitter may comprise a pellicle beam splitter, a cube beamsplitter, a dichroic mirror, a band filter or a longpass/shortpass filter.

[0094] The biometric device **120** may comprise a noncontact biometric device. The biometric device may comprise an interferometer. The interferometer may comprise a laser interferometer or a low coherence interferometer. The interferometer may comprise an optical biometer or an optical coherence tomographer (OCT).

[0095] The biometric data obtained by device **120** may comprise one or more of choroidal thickness; optical axial length (distance from the anterior corneal surface to the retinal pigment epithelium); vitreous chamber depth, anterior chamber depth, crystalline lens thickness, corneal thickness, retinal thickness (or layers within the retina), and scleral thickness. These biometric data may be acquired along any axis of the eye **30**OS, but will typically be acquired along the visual axis as the person being tested views the biometric device's fixation target **121** (not shown).

[0096] In the embodiment shown in FIG. **1**C the biometric device **120** comprises a Lenstar optical biometer. The Lenstar LS 900 **120** is a noncontact optical biometer based on the principle of optical low-coherence reflectometry. It provides a comprehensive range of ocular axial biometric measurements including corneal thickness (CT), anterior chamber depth (ACD), lens thickness (LT), and axial length (AxL) [distance from anterior cornea to retinal pigment epithelium]) simultaneously in a single measurement procedure.

[0097] To implement the ophthalmic lens design, an adaptive optics device **160** comprises one or more wavefront shapers **161**. The one or more wavefront shapers **161** may comprise one or more spatial light modulator **164** and/or one or more adaptive or deformable mirror **162**.

[0098] Typically, an adaptive or deformable mirror **162** is capable of implementing large stroke changes to a wavefront but lacks detail. A spatial light modulator **164** is theoretically capable of displaying any wavefront shape.

[0099] The embodiments shown in FIGS. **1**C and **3**A comprise one spatial light modulator **164** and one adaptive mirror **162**. In other embodiments, apparatus **100** may comprise two or more spatial light modulators **164** and/or two or more adaptive mirrors **162**.

[0100] The deformable or adaptive mirror **162** recreates the pre-determined wavefront by modifying the surface shape of a deformable membrane **163** (not shown). The adaptive mirror **162** is driven by one or more actuators **169** (not shown) to adjust the shape of the generated wavefront.

[0101] The spatial light modulator (SLM) **164** recreates the pre-determined wavefront shape by changing the refractive index and uses a modular method (diffractive optics) to display the wavefront pattern of a high amplitude.

[0102] Spatial light modulator **164** is comprised of a liquid crystal layer **165** (not shown) that changes refractive index in response to an array of underlying electrodes (not shown).

Spatial light modulator **164** comprises pixels or optical elements of 15×15 microns and a square 7.68×7.68 mm active area.

[0103] The adaptive optics device **160** may comprise a single SLM **164** only to shape the wavefront. However, two or more SLMs **164** may be preferred. The inventors hypothesise that multiple SLMs **164** may be used to induce axial changes with different wavelengths. In particular, the axial changes with wavefront modulation of blue light may be induced with a designated SLM **164**. The induced axial changes may then be measured with biometric device **120**.

[0104] Spatial light modulator **164** is operated by a controller **168** (not shown) to adjust the shape of the generated wavefront. The controller **168** is directed by computing device **200**. In the embodiments shown in FIGS. **1**C and **3**A controller **168** comprises a control box connected to the computer by a PCIEX16 slot. From the teaching herein a skilled person is readily able to select other suitable devices for controller **168**. In one embodiment, controller **168** may not be comprised in device **100** and the direction of SLM **164** is performed directly by computer **200**.

[0105] To take advantage of the capabilities of the different wavefront shapers **161**, when both a spatial light modulator **164** and a deformable mirror **162** are present, they may be located in series. The embodiments of FIGS. **1**C and **3**A show the spatial light modulator **164** and the one adaptive mirror **162** located in series.

[0106] The apparatus **100** has a field of view of 5.2 degrees and a wavelength range of 555 to 785 nm. The field of view may be increased by modifying the optics of the system **300**.

[0107] The adaptive optics device **160** further comprises a wavefront sensor **166** for directly measuring the implemented ophthalmic lens design.

[0108] The adaptive optics device **160** also comprises a plurality of optical elements **130**. The various components of the plurality of optical elements **130** direct the light beams **113**, **115**, **117**. From the teachings herein a skilled person is readily able to select suitable components for the plurality of optical elements **130**.

[0109] One component of the plurality of optical elements **130** is focus corrector **146** which comprises a Badal stage **148**. The Badal stage **148** comprises two or more Badal stage mirrors **150**.

[0110] The plurality of optical elements **130** may further comprise one or more relay lens set **152**; one or more mirrors **136**; one or more lenses **132**; one or more beam splitters **134**; and/or one or more cold mirrors **144**.

[0111] The adaptive optics device **160** further comprises one or more micro-displays **180**. Both a primary micro-display **180***a* and a secondary micro-display **180***b* may be present. The primary micro-display **180***a* may be viewable through the one or more wavefront shapers **161**. Each of the plurality of micro-displays **180** may comprise any suitable display such as, an LED or OLED display.

[0112] Each of the one or more micro-displays **180** may be individually or collectively synchronised to display vision tests including visual acuity and contrast sensitivity. Each of the one or more micro-displays **180** may also be individually or collectively synchronised to display a movie or collection of images of the viewer's choice.

[0113] Each of the one or more micro-displays **180** may display a fine reference scale and/or a grayscale. The grayscale may comprise 256 levels.

[0114] The secondary micro-display **180***b* may be aligned so that the image **184** displayed thereon overlays with an image **184** displayed on the primary micro-display **180***a*. The images displayed on the secondary micro-display **180***b* may be under independent optical control.

[0115] An image **184** displayed on a micro-display **180** may be manipulated with imposition of an optical design while the image displayed on the secondary display **180***b* may be used as a reference.

[0116] The optical elements **130** may further comprise an objective lens in front of secondary micro-display **180***b* to produce the same through-system magnification as in the primary micro-display **180***a*.

[0117] Apparatus **100** further comprises a fellow eye **30**OD viewer **420** comprising a display **436**. The fellow eye **30**OD display **436** may be synchronised with one or more micro-displays **180**. FIG. **1**D shows the subject view during testing without illustrating device **160**.

[0118] To make fellow eye **30**OD viewer **420** visible to eye **30**OD, device **100** further comprises fellow eye **30**OD optical elements **426**, which in the embodiment shown in FIG. **1**C comprises lens **428**, colour filter **430** and mirror **432**. The fellow eye **30**OD optical components **426**, or a portion thereof, may be comprised in a fellow eye **3**OD lens mount **424**. Mirror **432** is not located in the lens mount **424** and is located between the fellow eye **30**D lens mount **424** and the fellow eye **3**OD display **436**.

[0119] Apparatus **100** further comprises an illumination source **104**. In the embodiment shown in FIG. **1**C, illumination source **104** comprises a plurality of LEDs **106** arranged in a ring **108**.

[0120] FIG. **1**C also shows a lens mount **102** and a lens **103** positioned adjacent eye **30**OS before beam splitter **110**.

[0121] As shown in FIG. **3**B, the adaptive optics device **160** may further comprise an imaging device **170**, such as a digital camera, with its image plane conjugate to or replacing the retinal plane of the eye **30**OS. Imaging device **170** may be used to replace the eye **30**OS when studying the optical design's impact on image quality. Additional optical elements **130** may be added to allow the imaging device **170** to be conjugate with the retinal plane of the eye **30**OS whilst being tested.

[0122] As shown in FIG. **1**A, also comprised in device **160** is a pupil viewer **400**, such as a digital camera. The pupil viewer **400** may be positioned in a pupil tracking path **404**. The pupil tracking path **404** may comprise one or more pupil tracking beam splitter **134** which may be comprised in optical elements **130**. The pupil viewer **400** also comprises a pupil tracker illumination source **406** (not shown). The pupil tracker illumination source **406** illuminates at a near infrared wavelength. The near infrared wavelength may comprise 700 to 2500 nm; 800 to 1100 nm; or 900 to 1000 nm. In one embodiment the near infrared wavelength comprises 950 nm.

[0123] The apparatus and system may further comprise a super luminescent diode **154** to illuminate the eye **30**OS. The illumination may comprise a spot image on the retina **34** for measurement purposes.

[0124] The apparatus **100** and system **300** may further comprise a laser or superluminescent diode to provide illumination for alignment.

[0125] Part of system **300** is shown in FIG. **1**E. System **300** comprises one or more computing device **200** for controlling the two or more wavefront shapers **161** to produce the ophthalmic lens design and for powering and controlling displays **180***a*, **180***b*, **214**, **420**.

[0126] Display **214** displays the graphical user interface for system **300**.

[0127] Computing device **200** is then connected to primary micro-display **180***a* in the adaptive optics light path **114** and secondary micro-display **180***b* and fellow eye **30**OD viewer **420** in the clear optics light path **118**.

[0128] A second output port of the graphic card (not shown) of personal computing device **200** has been split into two channels with the same output (Maltese cross target, a movie or collection of images). By doing this, micro-displays **180***a* and **180***b* may be synchronised for the two eyes **30**OS, **30**OD.

[0129] The size, brightness and contrast of micro-displays **180***a*, **180***b* may be adjusted to match each other. Secondary micro-display **180***b* is set to run on non-colour mode which is the same as the primary micro-display **180***a*.

[0130] One embodiment of a method **500** for measuring an influence of ophthalmic lens design according to the invention is shown in FIG. **13**. At **502** an optical light path is split into an adaptive optics light path and an ocular biometric measurement light path. At **504** the ophthalmic lens design is implemented in an adaptive optics device positioned in the adaptive optics light path. Then, at **506**, biometric data is obtained in the ocular biometric measurement light path to measure the influence of the ophthalmic lens design.

[0131] One embodiment of a computing device **200** suitable for use in the present invention is shown in FIGS. **2**A and **2**B. In the embodiment shown computing device **200** comprises a computer module **201** comprising input devices such as a keyboard **202**, a mouse pointer device **203**, a scanner **226**, an external hard drive **227**, and a microphone **280**; and output devices including a printer **215**, a display device **214** and loudspeakers **217**. In some embodiments video display **214** may comprise a touchscreen.

[0132] A Modulator-Demodulator (Modem) transceiver device **216** may be used by the computer module **201** for communicating to and from a communications network **220** via a connection **221**. The network **220** may be a wide-area network (WAN), such as the Internet, a cellular telecommunications network, or a private WAN. Through the network **220**, computer module **201** may be connected to other similar computing devices **290** or server computers **291**. Where the connection **221** is a telephone line, the modem **216** may be a traditional "dial-up" modem. Alternatively, where the connection **221** is a high capacity (e.g.: cable) connection, the modem **216** may be a broadband modem. A wireless modem may also be used for wireless connection to network **220**.

[0133] The computer module **201** typically includes at least one processor **205**, and a memory **206** for example formed from semiconductor random access memory (RAM) and semiconductor read only memory (ROM). The module **201** also includes a number of input/output (I/O) interfaces including: an audio-video interface **207** that couples to the video display **214**, loudspeakers **217** and microphone **280**; an I/O interface **213** for the keyboard **202**, mouse **203**, scanner **226** and external hard drive **227**; and an interface **208** for the external modem **216** and printer **215**. In some implementations, modem **216** may be incorporated within the computer module **201**, for example within the interface **208**. The computer module **201** also has a local network interface **211** which, via a connection **223**, permits coupling of the computing device **200** to a local computer network **222**, known as a Local Area Network (LAN).

[0134] As also illustrated, the local network **222** may also couple to the wide network **220** via a connection **224**, which would typically include a so-called "firewall" device or device of similar functionality. The interface **211** may be formed by an Ethernet circuit card, a Bluetooth wireless arrangement or an IEEE 802.11 wireless arrangement or other suitable interface.

[0135] The I/0 interfaces **208** and **213** may afford either or both of serial and parallel connectivity, the former typically being implemented according to the Universal Serial Bus (USB) standards and having corresponding USB connectors (not illustrated).

[0136] Storage devices **209** are provided and typically include a hard disk drive (HDD) **210**. Other storage devices such as, an external HD **227**, a USB-RAM drive (not shown), memory cards (not shown), a disk drive (not shown) and a magnetic tape drive (not shown) may also be used. An optical disk drive **212** is typically provided to act as a non-volatile source of data. Portable memory devices, such as optical disks (e.g.: CD-ROM, DVD, Blu-Ray Disc), USB-RAM, external hard drives and floppy disks for example, may be used as appropriate sources of data to the computing device **200**. Another source of data to computing device **200** is provided by the at least one server computer **291** through network **220**.

[0137] The components **205** to **213** of the computer module **201** typically communicate via an interconnected bus **204** in a manner that results in a conventional mode of operation of computing device **200**. In the embodiment shown in FIGS. **2**A and **2**B, processor **205** is coupled to system bus **204** through connections **218** Similarly, memory **206** and optical disk drive **212** are coupled to the system bus **204** by connections **219**. Examples of computing devices **200** on which the described arrangements can be practiced include IBM-PC's and compatibles, Sun Sparc stations, Apple computers; smart phones; tablet computers or like a device comprising a computer module like computer module **201**. It is to be understood that when computing device **200** comprises a smart phone or a tablet computer, display device **214** may comprise a touchscreen and other input and output devices may not be included such as, mouse pointer device **201**; keyboard **202**; scanner **226**; and printer **215**.

[0138] FIG. **2**B is a detailed schematic block diagram of processor **205** and a memory **234**. The memory **234** represents a logical aggregation of all the memory modules, including the storage device **209** and semiconductor memory **206**, which can be accessed by the computer module **201** in FIG. **2**A.

[0139] The methods of the invention may be implemented using computing device **200** wherein the methods may be implemented as one or more software application programs **233** executable within computer module **201**. In particular, the steps of the methods of the invention may be effected by instructions **231** in the software carried out within the computer module **201**

[0140] The software instructions **231** may be formed as one or more code modules, each for performing one or more particular tasks. The software **233** may also be divided into two separate parts, in which a first part and the corresponding code modules performs the method of the invention and a second part and the corresponding code modules manage a graphical user interface between the first part and the user.

[0141] The software **233** may be stored in a computer readable medium, including in a storage device of a type described herein. The software is loaded into the computing device **200** from the computer readable medium or through network **221** or **223**, and then executed by computing device **200**. In one example the software **233** is stored on storage medium **225** that is read by optical disk drive **212**. Software **233** is typically stored in the HDD **210** or the memory **206**.

[0142] A computer readable medium having such software **233** or computer program recorded on it is a computer program product. The use of the computer program product in the computing device **200** preferably affects a device or apparatus for implementing the methods of the invention.

[0143] In some instances, the software application programs **233** may be supplied to the user encoded on one or more disk storage medium **225** such as a CD-ROM, DVD or Blu-Ray disc, and read via the corresponding drive **212**, or alternatively may be read by the user from the networks **220** or **222**. Still further, the software can also be loaded into the computing device **200** from other computer readable media. Computer readable storage media refers to any non-transitory tangible storage medium that provides recorded instructions and/or data to the computer module **201** or computing device **200** for execution and/or processing. Examples of such storage media include floppy disks, magnetic tape, CD-ROM, DVD, Blu-ray Disc, a hard disk drive, a ROM or integrated circuit, USB memory, a magneto-optical disk, or a computer readable card such as a PCMCIA card and the like, whether or not such devices are internal or external of the computer module **201**. Examples of transitory or non-tangible computer readable transmission media that may also participate in the provision of software application programs **233**, instructions **231** and/or data to the computer module **201** include radio or infra-red transmission channels as well as a network connection **221**, **223**, **334**, to another computer or networked device **290**, **291** and the Internet or an Intranet including email transmissions and information recorded on Websites and the like.

[0144] The second part of the application programs **233** and the corresponding code modules mentioned above may be executed to implement one or more graphical user interfaces (GUIs) to be rendered or otherwise represented upon display **214**. Through manipulation of, typically, keyboard **202**, mouse **203** and/or screen **214** when comprising a touchscreen, a user of computing device **200** and the methods of the invention may manipulate the interface in a functionally adaptable manner to provide controlling commands and/or input to the applications associated with the GUI(s). Other forms of functionally adaptable user interfaces may also be implemented, such as an audio interface utilizing speech prompts output via loudspeakers **217** and user voice commands input via microphone **280**. The manipulations including mouse clicks, screen touches, speech prompts and/or user voice commands may be transmitted via network **220** or **222**.

[0145] When the computer module **201** is initially powered up, a power-on self-test (POST) program **250** may execute. The POST program **250** is typically stored in a ROM **249** of the semiconductor memory **206**. A hardware device such as the ROM **249** is sometimes referred to as firmware. The POST program **250** examines hardware within the computer module **201** to ensure proper functioning, and typically checks processor **205**, memory **234** (**209**, **206**), and a basic input-output systems software (BIOS) module **251**, also typically stored in ROM **249**, for correct operation. Once the POST program **250** has run successfully, BIOS **251** activates hard disk drive **210**. Activation of hard disk drive **210** causes a bootstrap loader program **252** that is resident on hard disk drive **210** to execute via processor **205**. This loads an operating system **253** into RAM memory **206** upon which operating system **253** commences operation. Operating system **253** is a system level application, executable by processor **205**, to fulfil various high level functions, including processor management, memory management, device management, storage management, software application interface, and generic user interface.

[0146] Operating system **253** manages memory **234** (**209**, **206**) in order to ensure that each process or application running on computer module **201** has sufficient memory in which to execute without colliding with memory allocated to another process. Furthermore, the different types of memory available in the computing device **200** must be used properly so that each process can run effectively. Accordingly, the aggregated memory **234** is not intended to illustrate how particular segments of memory are allocated, but rather to provide a general view of the memory accessible by computer module **201** and how such is used.

[0147] Processor **205** includes a number of functional modules including a control unit **239**, an arithmetic logic unit (ALU) **240**, and a local or internal memory **248**, sometimes called a cache memory. The cache memory **248** typically includes a number of storage registers **244**, **245**, **246** in a register section storing data **247**. One or more internal busses **241** functionally interconnect these functional modules. The processor **205** typically also has one or more interfaces **242** for communicating with external devices via the system bus **204**, using a connection **218**. The memory **234** is connected to the bus **204** by connection **219**.

[0148] Application program **233** includes a sequence of instructions **231** that may include conditional branch and loop instructions. Program **233** may also include data **232** which is used in execution of the program **233**. The instructions **231** and the data **232** are stored in memory locations **228**, **229**, **230** and **235**, **236**, **237**, respectively. Depending upon the relative size of the instructions **231** and the memory locations **228-230**, a particular instruction may be stored in a single memory location as depicted by the instruction shown in the memory location **230**. Alternately, an instruction may be segmented into a number of parts each of which is stored in a separate memory location, as depicted by the instruction segments shown in the memory locations **228** and **229**.

[0149] In general, processor **205** is given a set of instructions **243** which are executed therein. The processor **205** then waits for a subsequent input, to which processor **205** reacts by executing another set of instructions. Each input may be provided from one or more of a number of sources, including data generated by one or more of the input devices **202**, **203**, or **214** when comprising a touchscreen, data received from an external source across one of the networks **220**, **222**, data retrieved from one of the storage devices **206**, **209** or data retrieved from a storage medium **225** inserted into the corresponding reader **212**. The execution of a set of the instructions may in some cases result in output of data. Execution may also involve storing data or variables to the memory **234**.

[0150] The disclosed arrangements use input variables **254** that are stored in the memory **234** in corresponding memory locations **255**, **256**, **257**, **258**. The described arrangements produce output variables **261** that are stored in the memory **234** in corresponding memory locations **262**, **263**, **264**, **265**. Intermediate variables **268** may be stored in memory locations **259**, **260**, **266** and **267**.

[0151] The register section **244**, **245**, **246**, the arithmetic logic unit (ALU) **240**, and the control unit **239** of the processor **205** work together to perform sequences of micro-operations needed to perform "fetch, decode, and execute" cycles for every instruction in the instruction set making up the program **233**. Each fetch, decode, and execute cycle comprises:

[0152] (a) a fetch operation, which fetches or reads an instruction **231** from memory location **228**, **229**, **230**;

[0153] (b) a decode operation in which control unit **239** determines which instruction has been fetched; and

[0154] (c) an execute operation in which the control unit **239** and/or the ALU **240** execute the instruction.

[0155] Thereafter, a further fetch, decode, and execute cycle for the next instruction may be executed. Similarly, a store cycle may be performed by which the control unit **239** stores or writes a value to a memory location **232**.

[0156] Each step or sub-process in the methods of the invention may be associated with one or more segments of the program **233**, and may be performed by register section **244-246**, the ALU **240**, and the control unit **239** in the processor **205** working together to perform the fetch, decode, and execute cycles for every instruction in the instruction set for the noted segments of program **233**.

[0157] One or more other computers **290** may be connected to the communications network **220** as seen in FIG. 2A. Each such computer **290** may have a similar configuration to the computer module **201** and corresponding peripherals.

[0158] One or more other server computers **291** may be connected to the communications network **220**. These server computers **291** respond to requests from the personal device or other server computers to provide information.

[0159] Method **500** may alternatively be implemented in dedicated hardware such as one or more integrated circuits performing the functions or sub functions of the described methods. Such dedicated hardware may include graphic processors, digital signal processors, or one or more microprocessors and associated memories.

[0160] Software **233** and processor **205** may operate on deformable mirror **162** and spatial light modulator **164** to quickly implement and test optical designs without the need to fabricate lenses.

[0161] The invention provides an ophthalmic lens comprising the ophthalmic lens design implemented according to the method **500** of the invention.

[0162] Further, the invention provides a method for optimising a lens design using the method **500**, the apparatus **100** and/or the system **300** of the invention. The invention additionally provides an ophthalmic lens comprising the optimised lens design.

EXAMPLES

Adaptive Optics System for Testing of Visual Acuity and Contrast Sensitivity

[0163] The optical layout of the adaptive optics (AO) device **160** for the testing of visual performance according to one embodiment of the invention is shown in FIG. **3**A. The integration of device **160** into apparatus **100** according to various embodiments of the invention is shown in FIGS. **1**A, **1**B and **1**C. The primary micro-display **180***a* comprising screen **182** was programmed to display vision tests including visual acuity and contrast sensitivity.

[0164] Customized software based on a staircase algorithm was used to control the size of an E target **20** (see FIG. **3**C) to test visual acuity, or the contrast level of the 'E' target **20** was varied to measure contrast threshold. The task for the subject was a four alternative choice with the subject pressing a keypad button to indicate if the E target **20** was oriented up, down, left or right. The staircase algorithm then incremented the size or contrast of the E target **20** based on the subject's correct or incorrect response to estimate the threshold resolution. Between target presentations, screen **182** displayed a mask **20***b* of grey random noise with an equal average contrast to the E target **20**. This is a psychophysical technique to minimize adaptation effects and after-images between presentations. The E target **20** was surrounded by flanking bars **20***c* that provided a lateral interaction similar to lines of letters displayed on letter acuity charts.

Testing Visual Acuity

[0165] The Tumbling E test target **20** was used in the adaptive optics device **160** to test high contrast photopic visual acuity with applied lens designs (two-zone, centre-distance concentric bifocals). Visual acuity was tested without any time limit Eight healthy young subjects participated. Measurements were only performed in the left eye **30**OS.

[0166] As a baseline measurement visual acuity was also measured with the subject's best distance sphero-cylinder correction.

[0167] As shown in FIG. **5**, increasing peripheral power +2D caused a loss of high contrast visual acuity. However as the peripheral power continued to increase, the relative effect on visual acuity plateaus, so that by +4D peripheral plus, the visual acuity loss becomes relatively constant.

Testing Contrast Sensitivity with Applied Designs

[0168] The aim of this study was to test the effect of applied lens designs on contrast sensitivity.

[0169] All four subjects were given a ten minute practice section on the device **160** with the contrast sensitivity test. After the subjects became familiar with the testing procedure, the experimental operator induced the applied lens designs of different level of plus power to the subject's left eye **30**OS. The order of testing was randomized. During testing, the subjects viewed an 'E' target **20** of fixed sizes displayed on the OLED micro-display **180***a* and performed the CS test without time limits

[0170] The task was a four alternative choice with the subject pressing a keypad button to indicate if the E target **20** was oriented up, down, left or right. In this experiment, CS tests were performed on the subjects with three different letter sizes of 0.3, 0.4 and 0.6 logMAR.

[0171] Increasing the peripheral power decreased the subject's contrast sensitivity (i.e. a higher contrast threshold).

[0172] As shown in FIG. **6**, unlike the VA (Visual Acuity) results, the CS (Contrast Sensitivity) were further reduced as higher amounts of plus power up to +6D were used in the peripheral zone.

[0173] Peripheral plus power showed a stronger effect on CS when the subject was viewing targets **20** with higher spatial frequency content (smaller letter sizes of 0.3 and 0.4 logMAR).

Secondary Micro-Display

[0174] As shown in FIG. **3**B a secondary micro-display **180***b* with the same specifications as micro-display **180***a* was added to adaptive optics device **160**. The secondary micro-display **180***b* was linked with the system axis by optical elements **130** comprising lenses **132**, cold mirrors **144** and pellicle beamsplitters (PB**2**) **134**.

[0175] The objective lens **132** in front of secondary micro-display **180***b* was chosen to produce the same through-system magnification as micro-display **180***a*.

[0176] The modified system **160** uses two micro-displays **180***a* and **180***b* aligned so that the images or screen targets **184***a* and **184***b* displayed thereon overlay each other, but each screen target **184***a* and **184***b* is under independent optical control.

Integration of Adaptive Optics System with Simultaneous Measurements of Choroidal Response

[0177] An adaptive optics device **160** comprising an adaptive or deformable mirror **162** and spatial light modulator **164** was combined with an ocular biometric device **120** to simultaneously test the effect of experimental lens designs on axial length/choroidal thickness at regular intervals during exposure to the optical design and again during the recovery period after exposure to the optical design had ceased. Advantageously, this approach provided the opportunity to test new optical designs without the need to manufacture the ophthalmic lenses.

[0178] Studies of the optical designs have been systematically varied in the adaptive optics device **160**, including parameters such as, location and area of the plus optical power in relation to lens centre and the progression of power (rate of change). Measurements of choroidal thickness and axial length were performed simultaneously when the subject is viewing through the ophthalmic lens design induced by the adaptive optics device **160**. Various retinal locations can be measured including at the fovea and at various locations in the retinal periphery.

[0179] The adaptive optics device **160** for basic vision research comprises the primary components of a Mirao adaptive mirror **162** and HASO Hartmann Shack wavefront sensor **166**. The Mirao adaptive mirror **162** can be accurately calibrated to produce aberrations such as spherical aberration. However because the adaptive mirror **162** is driven by fifty-two actuators **169** (not shown) it has limited ability to produce optical designs with steep gradients of power.

[0180] To provide a device **160** with the capacity to simulate a wide range of challenging optical designs, a spatial light modulator **164** was added. In this embodiment, the SLM **164** was obtained from Boulder Nonlinear Systems Inc. Designs to produce abrupt power changes such as two zone concentric bifocals with a +10D peripheral zone.

[0181] As shown in FIGS. **1**C and **3**A the SLM **164** was integrated into adaptive optics device **160** in series with the existing adaptive or deformable mirror **162**. Advantageously, this results in the power of both adaptive optics elements to create a wide range of optical designs.

[0182] The spatial light modulator **164** is composed of a liquid crystal **165** (not shown) layer that changes refractive index in response to an array of underlying electrodes **171** with a liquid crystal pixel/element size of 15×15 microns across a square 7.68×7.68 mm active area.

[0183] Validation testing of the adaptive optics device **160** output was conducted with a variety of optical designs. As shown in FIGS. **4**A and **4**B, both vertical coma and spherical aberration were accurately implemented in the spatial light modulator **164**, when directly measured using the HASO wavefront sensor **166**. The adaptive optics device **160** combining the adaptive mirror **162** and spatial light modulator **164** has provided the capacity to quickly produce complex optical designs and then to reliably test a range of aspects of visual performance and axial length and or choroidal response.

Development of the Combined Adaptive Optics Stimulus System with Simultaneous Measurements of Axial Length/Choroidal Thickness

[0184] To test the response of the axial length **38** of the eye **30**OS to optical designs with the adaptive optics device **160** required a series of developments. These issues included:

[0185] 1. How to control the accommodation response of the tested eye.

[0186] 2. How to measure the axial length of the eye while simultaneously exposing the eye to the optical design.

[0187] 3. What visual task would the subject undertake while viewing through the optics for up to an hour.

[0188] 4. How to maintain the subject aligned within the optical system for up to an hour of continuous testing.

[0189] The apparatus **100** used is illustrated in the FIGS. **1**A, **1**B, **1**C and FIG. **3**A, **3**B and allows the control of accommodation and simultaneous viewing of the measurement light path **116** and the adaptive optics light path **114**. If the fellow eye **30**OD is occluded and the tested eye **30**OS views target **182**, the tested eye **30**OS will accommodate based on the optical design generated by the adaptive optics system **160** and the Badal lens system settings. For example, this can range from zero accommodation demand (far viewing) to a high level of accommodation demand (e.g. 5 D) to simulate near viewing at 20 cm.

[0190] Accommodation can also be controlled by using the fellow non-tested eye **30**OD to focus on a target **184***b* as shown in FIG. **1**C. If this target **184***b* viewed by the fellow eye **3**OD is clear, it will dominate the accommodation response of the two eyes **30**OS, **30**OD (the tested eye **30**OS may be blurred by the optical design under test).

[0191] Accommodation response of the tested eye **30**OS can be checked with the HASO wavefront sensor **166** at any time during the testing period. By using a beam splitter **134** between the tested eye **30**OS and the biometric device **120**, the tested eye **30**OS can simultaneously view the ocular biometric measurement light path **116** of the biometric device **120** and the screen target **184***a*.

[0192] The subject is required to view a target **184** through the adaptive optics device **160** for up to an hour. During measurements of axial length **38** with the Lenstar **120** this process requires accurate and steady fixation so as to align the measurement light beam **117** of the Lenstar **120** with the foveal axis of the tested eye **30**OS. To ensure steady fixation a Maltese cross target **20** was presented as a screen target **184** on a micro-display screen **182** and the centre of the measurement beam **117** (appears to the subject as a red dot) was aligned via joystick control with the centre of the Maltese cross displayed on micro-display **180***a*. The beam splitter **110** before the Lenstar **120** allows the subject to see both the micro-display **180***a* and the Lenstar measurement light beam **117** simultaneously.

[0193] If accommodation control is also required with the fellow eye **30**OD, then the fellow eye **30**OD viewer **420** is synchronized to the tested eye micro-display **180***a* and both eyes **30**OS and **30**OD see elements of the cross pattern simultaneously (this is called dichoptic viewing where both eyes see similar aspects of a scene, but presented through different optical paths).

[0194] Since viewing the Maltese cross pattern or a static image for up to an hour in the adaptive optics system **160** is tedious, the micro-display **180***a* and far target monitor/fellow eye **30**OD viewer **420** are used to synchronously present a movie of the subject's choice. The subject then sees the movie through the ophthalmic test design via the adaptive optics affecting the tested eye **30**OS with the fellow eye **3**OD occluded. Alternately the movie can be viewed by both eyes **30**OD and **30**OS, with the ophthalmic test design affecting the image seen with the tested eye **30**OS that is viewing via the adaptive optics device **160**, while the fellow eye **30**OD can be optimally corrected for clear vision. This arrangement is shown in FIG. **1**E and illustrates computer **200** that may be used to control deformable mirror **162** and the spatial light modulator **164**.

[0195] When the subject views the micro-display target **184** through the adaptive optics device **160** it is important that they remain steady and the pupil **32** remains well centered with respect to the optical light path **112** of the adaptive optics device **160**. Since the myopia control optical designs often have rapid power changes across the pupil **32**, misalignment of the optics can substantially change the type and level of the components of the test wavefront.

[0196] To minimize this problem of patient and pupil misalignment, the inventors developed a pupil tracker **400** comprising a pupil tracker path **404** in the adaptive optics device **160** that provides real time feedback to the computing device then to the controller **168** for the spatial light modulator **164**. The pupil tracker illumination source **406** was chosen as 950 nm (near infrared) so as to not be visible to the subject and therefore not to cause pupil constriction.

[0197] The pupil tracking camera **402** provides tracking of the centre of the pupil **32** at a frequency of 30 Hz that is sent to the spatial light modulator controller **168**. The controller **168** then adjusts the position of the wavefront generated by the spatial light modulator **164** on its active surface in real time, so that the wavefront (test optical design) essentially moves with the eye **30**OS to stay centered on the pupil **32**. In this way, over the course of an hour of testing, the subject can move slightly during the testing and still be exposed to the appropriate optical wavefront.

[0198] The effect of pupil tracking and re-centering the wavefront pattern with the subject's pupil **32** is shown in FIG. **7**. In both examples of 0.25 mm and 0.50 mm pupil offset, the SLM re-centered the wavefront of the applied optical design to the subject's pupil **32**, resulting in a much lower amount of residual wavefront error, compared to the results without pupil tracking.

[0199] FIG. **8** shows the pupil location of a subject over a **30** min period when viewing a Maltese cross target through the system **300**. A heavy and steady headrest with a chinrest and headband is used without the use of a bite bar.

[0200] The repeatability of results was tested through the adaptive optics device **160** with four optical conditions (+3D defocus, −3D defocus, +3D longitudinal spherical aberration and −3D longitudinal spherical aberration) over 40 minutes testing. The same subject completed all four optical conditions on two occasions, once using the Maltese cross as fixation target **184** for 40 minutes and again watching a movie throughout the test for 40 minutes. Whenever axial length measurements were taken, the movie was switched to back to the Maltese cross to ensure steady fixation.

[0201] The results in FIGS. **9** and **10** show a good correlation between changes in axial length **38** in both testing conditions. The minus defocus and minus spherical aberration both cause the tested eye **30**OS to get longer and the positive defocus and positive spherical aberration both cause the tested eye **30**OS to shorten.

Axial Length Measurements with the Lenstar LS900

[0202] To determine the geometric distances between peaks in the A-scan, the Lenstar instrument **120** converts optical path lengths into geometric lengths, using assumed refractive indices of the ocular media. The axial resolution is about ten microns for a single A-scan.

[0203] An A-scan from a single measurement from a typical subject using Lenstar instrument **120** allows a range of ocular biometric dimensions to be derived from each measurement. A total of five measurements were typically taken and the results later averaged. Following data collection, the A-scan data originating from the posterior eye from each measurement can be manually analysed using the instrument's software to determine the retinal and choroidal thickness. However, choroidal thickness can be accurately derived from spectral domain optical coherence tomography scans with a resolution of about 4-5 microns.

Optimal Subject Testing Conditions to Understand the Effect of Optical Designs on Axial Length/Choroidal Response

[0204] Studies with the adaptive optics device **160** concentrated on understanding the appropriate time period required for "washout" of the effects of prior visual tasks and the prior environment on the outcomes with optical designs viewed through the adaptive optics device **160**. Studies by the inventors have shown that accommodation causes the choroid **40** to thin slightly and the axial length **38** to increase (during accommodation), with a regression of about five minutes after ten minutes of accommodation. Other factors thought to influence the choroid thickness **42** are certain medications, nicotine, and caffeine.

[0205] The inventors used a washout period of twenty minutes before exposure to the optical designs is commenced. During this time the subjects sit in a room in low illumination with optimal refractive correction being worn and watch TV at a far accommodation distance of 6 m, to relax accommodation and to adapt the retina **34** to the room illuminance. Subjects are routinely questioned about their medication, caffeine and nicotine use.

[0206] Since the human eye shows diurnal variation in axial length **38** and choroidal thickness **42** (the eye is longest and the choroid thinnest at around noon), the inventors endeavour to always test subjects at the same time of day to avoid confounding effects from underlying diurnal rhythms.

Adaptive Optics Study of Concentric Design

[0207] The purpose of this study was to investigate the time course and magnitude of changes of axial length **38** under the influence of a concentric bifocal ophthalmic design, and +3D spherical defocus introduced to the eye **30**OS by means of adaptive optics.

[0208] All subjects were tested with both defocus conditions. The subjects were masked to the type of defocus used in each trial.

[0209] Sixteen young (aged 18-30 years) healthy adults were recruited. The optical defocus conditions were tested on different days and at approximately the same of the day to minimize the influence of diurnal variations on axial length.

[0210] After a 40 min exposure to the different positive defocus conditions (+3D defocus and the concentric bifocal), significant change (shortening of about 10 microns) in axial length (AxL) **38** was observed. Subjects showed a similar shortening response to both the +3D defocus and concentric bifocal (2 mm central plano zone with +6D periphery). Once exposure to the +3D defocus or concentric bifocal conditions via the adaptive optics are stopped at 40 minutes and the optical correction of the eye is now optimally in focus, the axial length of the eye begins to recover towards its original baseline levels over the next 15 minutes. Results are shown in FIG. **11**.

[0211] The changes in axial length **38** suggests that the eye is capable of rapidly (within 40 mins) detecting the optical blur introduced via the adaptive optics and altering its axial length.

[0212] The present invention has shown that within forty minutes, the eye shows reliable changes in its axial length **38** which allows the development of an understanding of the lens design features which are detected by the tested eye **30**OS to adjust short-term eye length.

[0213] Advantageously, the present invention overcomes the need to manufacture test ophthalmic lenses and through the pupil tracking software function, allows the optical design to be consistently located coincident with the centre of the pupil.

[0214] The findings herein have provided important guidance for the development of a model to guide the optimization of ophthalmic lens designs to potentially control long term eye growth.

[0215] In this specification, the terms “comprises”, “comprising” or similar terms are intended to mean a non-exclusive inclusion, such that an apparatus that comprises a list of elements does not include those elements solely, but may well include other elements not listed.

[0216] Throughout the specification the aim has been to describe the invention without limiting the invention to any one embodiment or specific collection of features. Persons skilled in the relevant art may realize variations from the specific embodiments that will nonetheless fall within the scope of the invention.

1.-**22**. (canceled)

23. A method for measuring an influence of an ophthalmic lens design comprising:

splitting an optical light beam into a wavefront measurement light path and a wavefront modulation light path;

implementing the ophthalmic lens design in an adaptive optics device positioned in the wavefront modulation light path; and

obtaining ocular biometric data of the influence of the ophthalmic lens design in an ocular biometric light path to measure the influence of the ophthalmic lens design.

24. The method of claim **23**, wherein the adaptive optics device comprises one or more wavefront shapers.

25. The method of claim **24**, wherein the one or more wavefront shapers comprise one or more spatial light modulators and/or one or more adaptive mirrors.

26. The method of claim **25**, wherein the one or more spatial light modulators comprise a liquid crystal layer that changes refractive index for optical modulation, in response to an array of underlying electrodes.

27. The method of claim **25**, wherein the one or more adaptive mirrors are driven by one or more actuators to adjust the shape of a generated wavefront.

28. The method of claim **24**, wherein the one or more wavefront shapers comprise one or more spatial light modular in series or the one or more wavefront shapers comprise one or more spatial light modulator in combination with one or more adaptive mirrors.

29. The method of claim **23**, wherein the adaptive optics device further comprises a wavefront sensor.

30. An apparatus for measuring an influence of an ophthalmic lens design comprising:

a beam splitter which splits an optical light path into a wavefront measurement light path and a wavefront modulation light path;

an adaptive optics device positioned in the wavefront modulation light path to implement the ophthalmic lens design; and

an ocular biometric device positioned in an ocular biometric measurement light path to obtain ocular biometric data of the influence of the ophthalmic lens design.

31. A method for assembling the apparatus of claim **30**, the method comprising:

installing a beam splitter to split an optical light path into a wavefront measurement light path and a wavefront modulation light path;

positioning an adaptive optics device in the wavefront modulation light path to implement the ophthalmic lens design; and

positioning an ocular biometric device in the ocular biometric measurement light path to obtain ocular biometric data.

32. The apparatus of claim **30**, wherein the adaptive optics device comprises one or more wavefront shapers.

33. The apparatus of claim **32**, wherein the one or more wavefront shapers comprise one or more spatial light modulators and/or one or more adaptive mirrors.

34. The apparatus of claim **33**, wherein the one or more spatial light modulators comprise a liquid crystal layer that changes refractive index for optical modulation, in response to an array of underlying electrodes.

35. The apparatus of claim **33**, wherein the one or more adaptive mirrors are driven by one or more actuators to adjust the shape of a generated wavefront.

36. The apparatus of claim **32**, wherein the one or more wavefront shapers comprise one or more spatial light modulars in series or the one or more wavefront shapers comprise one or more spatial light modulators in combination with one or more adaptive mirrors.

37. The apparatus of claim **30**, wherein the adaptive optics device further comprises a wavefront sensor.

38. A system for measuring an influence of an ophthalmic lens design comprising:

a beam splitter for splitting an optical light path into a wavefront modulation light path and a wavefront measurement light path;

- an adaptive optics device positioned in the wavefront modulation light path;
- one or more processors for controlling the adaptive optics device to implement the ophthalmic lens design; and
- an ocular biometric device positioned in an ocular biometric measurement light path for obtaining ocular biometric data of the influence of the ophthalmic lens design.

39. A method for assembling the system of claim **38**, the method comprising:

- installing a beam splitter to split an optical light path into a wavefront measurement light path and a wavefront modulation light path;
- positioning an adaptive optics device in the wavefront modulation light path to implement the ophthalmic lens design;
- connecting one or more processor to control the adaptive optics device to implement the ophthalmic lens design; and
- positioning an ocular biometric device in the ocular biometric measurement light path to obtain ocular biometric data.

40. The system of claim **38**, wherein the adaptive optics device comprises one or more wavefront shapers.

41. The system of claim **40**, wherein the one or more wavefront shapers comprise one or more spatial light modulators and/or one or more adaptive mirrors.

42. The system of claim **41**, wherein the one or more spatial light modulators comprise a liquid crystal layer that changes refractive index for optical modulation, in response to an array of underlying electrodes.

43. The system of claim **41**, wherein the one or more adaptive mirrors are driven by one or more actuators to adjust the shape of a generated wavefront.

44. The system of claim **40**, wherein the one or more wavefront shapers comprise one or more spatial light modulars in series or wherein the one or more wavefront shapers comprise one or more spatial light modulators in combination with one or more adaptive mirrors.

45. The system of claim **38**, wherein the adaptive optics device further comprises a wavefront sensor.

46. An ophthalmic lens comprising the ophthalmic lens design implemented according to the method of claim **1**.

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