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(54) **IMAGE-GUIDED DOCKING FOR
OPHTHALMIC SURGICAL SYSTEMS**

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4,907,586 A	3/1990	Bille et al.
5,048,946 A	9/1991	Sklar et al.
5,049,147 A	9/1991	Danon
5,054,907 A	10/1991	Sklar et al.
5,098,426 A	3/1992	Sklar et al.
5,139,022 A	8/1992	Lempert
5,246,435 A	9/1993	Bille et al.
5,255,025 A	10/1993	Volk
5,286,964 A	2/1994	Fountain
5,321,501 A	6/1994	Swanson et al.

(Continued)

FOREIGN PATENT DOCUMENTS

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EP	1444946 A1	8/2004
JP	2002345758	12/2002

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OTHER PUBLICATIONS

U.S. Appl. No. 90/006,816, filed Feb. 27, 2007, Swanson et al.

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A61B 3/14 (2006.01)

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(52) **U.S. Cl.** **351/206; 351/208; 351/246**

(58) **Field of Classification Search** 351/205–206,
351/200, 208–210, 221–223, 246
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

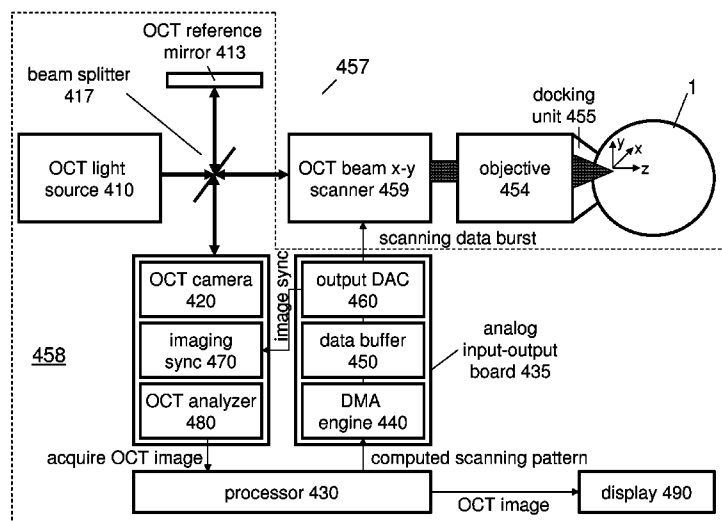
4,164,222 A	8/1979	Prokhorov et al.
4,198,143 A	4/1980	Karasawa
4,235,529 A	11/1980	Kawase et al.
4,465,348 A	8/1984	Lang
4,520,816 A	6/1985	Schachar et al.
4,533,222 A	8/1985	Ishikawa
4,538,608 A	9/1985	L'Esperance, Jr.
4,554,917 A	11/1985	Tagnon
4,638,801 A	1/1987	Daly et al.
4,764,005 A *	8/1988	Webb et al. 351/205
4,881,808 A	11/1989	Bille et al.
4,901,718 A	2/1990	Bille et al.

Primary Examiner — Dawayne A Pinkney

(57) **ABSTRACT**

A docking method for an ophthalmic system may include the steps of aligning a docking unit of the ophthalmic system and an eye; generating an image of an internal structure of the eye by an imaging system; improving an alignment of the docking unit with the internal structure of the eye in relation to the generated image; and docking the docking unit to the eye. The generating the image step may include computing scanning data by a processor corresponding to a scanning pattern; storing the scanning data in a data buffer; transferring the scanning data by the data buffer to an output module; outputting scanning signals by the output module to one or more scanners based on the scanning data; and scanning an imaging beam with the one or more scanners according to the scanning signals.

40 Claims, 12 Drawing Sheets



U.S. PATENT DOCUMENTS				
5,336,215 A	8/1994	Hsueh et al.	7,370,966 B2	5/2008 Fukuma et al.
5,439,462 A	8/1995	Bille et al.	7,371,230 B2	5/2008 Webb et al.
5,493,109 A	2/1996	Wei et al.	7,372,578 B2	5/2008 Akiba et al.
5,549,632 A	8/1996	Lai	7,388,672 B2	6/2008 Zhou et al.
5,656,186 A	8/1997	Mourou et al.	7,390,089 B2	6/2008 Loesel et al.
5,738,676 A	4/1998	Hammer et al.	7,400,410 B2	7/2008 Baker et al.
5,779,696 A	7/1998	Berry et al.	7,402,159 B2	7/2008 Loesel et al.
5,795,295 A	8/1998	Hellmuth et al.	7,426,037 B2	9/2008 Ostrovsky et al.
5,936,706 A	8/1999	Takagi	7,433,046 B2	10/2008 Everett et al.
5,954,648 A	9/1999	Van Der Brug	7,452,077 B2	11/2008 Meyer et al.
5,954,711 A	9/1999	Ozaki et al.	7,452,080 B2	11/2008 Wiltberger et al.
5,994,690 A	11/1999	Kulkarni et al.	7,461,658 B2	12/2008 Jones et al.
6,004,314 A	12/1999	Wei et al.	7,466,423 B2	12/2008 Podoleanu et al.
6,095,648 A	8/2000	Birngruber et al.	7,470,025 B2	12/2008 Iwanaga
6,099,522 A	8/2000	Knopp et al.	7,477,764 B2	1/2009 Haisch
6,137,585 A	10/2000	Hitzenberger et al.	7,480,058 B2	1/2009 Zhao et al.
6,254,595 B1	7/2001	Juhasz et al.	7,480,059 B2	1/2009 Zhou et al.
6,288,784 B1	9/2001	Hitzenberger et al.	7,488,070 B2	2/2009 Hauger et al.
6,314,311 B1	11/2001	Williams et al.	7,488,930 B2	2/2009 Ajgaonkar et al.
6,317,616 B1	11/2001	Glossop	7,492,466 B2	2/2009 Chan et al.
6,337,925 B1	1/2002	Cohen et al.	7,503,916 B2	3/2009 Shimmick
6,377,349 B1	4/2002	Fercher	7,508,525 B2	3/2009 Zhou et al.
6,379,005 B1	4/2002	Williams et al.	7,535,577 B2	5/2009 Podoleanu et al.
6,451,009 B1	9/2002	Dasilva et al.	7,537,591 B2	5/2009 Feige et al.
6,454,761 B1	9/2002	Freedman	7,557,928 B2	7/2009 Ueno
6,497,701 B2	12/2002	Shimmick et al.	7,575,322 B2	8/2009 Somani
6,529,758 B2	3/2003	Shahidi	7,593,559 B2	9/2009 Toth et al.
6,579,282 B2	6/2003	Bille et al.	7,602,500 B2	10/2009 Izatt et al.
6,623,476 B2	9/2003	Juhasz et al.	7,604,351 B2	10/2009 Fukuma et al.
6,687,010 B1	2/2004	Horii et al.	7,614,744 B2	11/2009 Abe
6,730,074 B2	5/2004	Bille et al.	7,630,083 B2	12/2009 de Boer et al.
6,741,359 B2	5/2004	Wei et al.	7,631,970 B2	12/2009 Wei
6,751,033 B2	6/2004	Goldstein et al.	7,633,627 B2	12/2009 Choma et al.
6,755,819 B1	6/2004	Waelti	7,643,152 B2	1/2010 de Boer et al.
6,763,259 B1	7/2004	Hauger et al.	2001/0022648 A1	9/2001 Lai
6,769,769 B2	8/2004	Podoleanu et al.	2002/0013574 A1	1/2002 Elbrecht et al.
6,775,007 B2	8/2004	Izatt et al.	2002/0082466 A1	6/2002 Han
6,863,667 B2	3/2005	Webb et al.	2002/0097374 A1	7/2002 Payne et al.
6,887,232 B2	5/2005	Bille	2002/0133145 A1	9/2002 Gerlach et al.
6,899,707 B2	5/2005	Scholler et al.	2002/0198516 A1	12/2002 Knopp
6,932,807 B1	8/2005	Tomita et al.	2003/0206272 A1	11/2003 Cornsweet et al.
6,991,629 B1	1/2006	Juhasz et al.	2004/0039378 A1	2/2004 Lin
6,996,905 B2	2/2006	Meguro	2004/0059321 A1	3/2004 Knopp et al.
7,006,232 B2	2/2006	Rollins et al.	2004/0151466 A1	8/2004 Crossman-Bosworth et al.
7,018,376 B2	3/2006	Webb et al.	2004/0243233 A1	12/2004 Phillips
7,027,233 B2	4/2006	Goldstein et al.	2005/0010109 A1	1/2005 Faul
7,061,622 B2	6/2006	Rollins et al.	2005/0015120 A1	1/2005 Seibel et al.
7,072,045 B2	7/2006	Chen et al.	2005/0021011 A1	1/2005 LaHaye
7,072,047 B2	7/2006	Westphal et al.	2005/0173817 A1	8/2005 Fauver et al.
7,079,254 B2	7/2006	Kane et al.	2005/0192562 A1	9/2005 Loesel et al.
7,102,756 B2	9/2006	Izatt et al.	2005/0201633 A1	9/2005 Moon et al.
7,113,818 B2	9/2006	Podoleanu et al.	2005/0203492 A1	9/2005 Nguyen et al.
7,126,693 B2	10/2006	Everett et al.	2005/0215986 A1	9/2005 Chernyak et al.
7,130,054 B2	10/2006	Ostrovsky et al.	2005/0284774 A1	12/2005 Mordaunt
7,133,137 B2	11/2006	Shimmick	2005/0286019 A1	12/2005 Wiltberger et al.
7,139,077 B2	11/2006	Podoleanu et al.	2005/0288745 A1	12/2005 Andersen et al.
7,145,661 B2	12/2006	Hitzenberger	2006/0020172 A1	1/2006 Luerssen et al.
7,148,970 B2	12/2006	de Boer	2006/0077346 A1	4/2006 Matsumoto
7,184,148 B2	2/2007	Alphonse	2006/0100613 A1	5/2006 McArdle et al.
7,207,983 B2	4/2007	Hahn et al.	2006/0179992 A1	8/2006 Kermani
7,248,371 B2	7/2007	Chan et al.	2006/0187462 A1	8/2006 Srinivasan et al.
7,268,885 B2	9/2007	Chan et al.	2006/0195076 A1*	8/2006 Blumenkranz et al. 606/4
7,280,221 B2	10/2007	Wei	2006/0206102 A1	9/2006 Shimmick
7,307,733 B2	12/2007	Chan et al.	2007/0013867 A1	1/2007 Ichikawa
7,310,150 B2	12/2007	Guillermo et al.	2007/0121069 A1	5/2007 Andersen et al.
7,312,876 B2	12/2007	Chan et al.	2007/0126985 A1	6/2007 Wiltberger et al.
7,329,002 B2	2/2008	Nakanishi	2007/0129709 A1	6/2007 Andersen et al.
7,330,270 B2	2/2008	O'Hara et al.	2007/0129775 A1	6/2007 Mordaunt et al.
7,330,273 B2	2/2008	Podoleanu et al.	2007/0147730 A1	6/2007 Wiltberger et al.
7,335,223 B2	2/2008	Obrebski	2007/0173791 A1	7/2007 Raksi
7,336,366 B2	2/2008	Choma et al.	2007/0173794 A1	7/2007 Frey et al.
7,342,659 B2	3/2008	Horn et al.	2007/0173795 A1	7/2007 Frey et al.
7,347,548 B2	3/2008	Huang et al.	2007/0185475 A1	8/2007 Frey et al.
7,352,444 B1	4/2008	Seams et al.	2007/0189664 A1	8/2007 Andersen et al.
7,355,716 B2	4/2008	de Boer et al.	2007/0216909 A1	9/2007 Everett et al.
7,364,296 B2	4/2008	Miller et al.	2007/0219541 A1	9/2007 Kurtz
7,365,856 B2	4/2008	Everett et al.	2007/0230520 A1	10/2007 Mordaunt et al.
7,365,859 B2	4/2008	Yun et al.	2007/0291277 A1	12/2007 Everett et al.
			2007/0299429 A1	12/2007 Amano

2008/0033406	A1	2/2008	Andersen et al.	
2008/0049188	A1	2/2008	Wiltberger et al.	
2008/0055543	A1	3/2008	Meyer et al.	
2008/0056610	A1	3/2008	Kanda	
2008/0071254	A1	3/2008	Lummis et al.	
2008/0088795	A1	4/2008	Goldstein et al.	
2008/0100612	A1	5/2008	Dastmalchi et al.	
2008/0281303	A1	11/2008	Culbertson et al.	
2008/0281413	A1	11/2008	Culbertson et al.	
2008/0319427	A1	12/2008	Palanker	
2009/0012507	A1	1/2009	Culbertson et al.	
2009/0088734	A1	4/2009	Mordaunt	
2009/0131921	A1	5/2009	Kurtz et al.	
2009/0149742	A1	6/2009	Kato et al.	
2009/0157062	A1	6/2009	Hauger et al.	
2009/0161827	A1*	6/2009	Gertner et al.	378/65
2009/0168017	A1	7/2009	O'Hara et al.	
2009/0268161	A1	10/2009	Hart et al.	
2010/0004641	A1	1/2010	Frey et al.	
2010/0004643	A1	1/2010	Frey et al.	
2010/0007848	A1	1/2010	Murata	
2010/0022994	A1	1/2010	Frey et al.	
2010/0022995	A1	1/2010	Frey et al.	
2010/0022996	A1	1/2010	Frey et al.	
2010/0042079	A1	2/2010	Frey et al.	
2010/0110377	A1	5/2010	Maloca et al.	
2010/0324543	A1	12/2010	Kurtz et al.	
2011/0022036	A1	1/2011	Frey et al.	
2011/0118609	A1	5/2011	Goldshleger et al.	
2011/0319873	A1	12/2011	Raksi et al.	
2012/0274903	A1*	11/2012	Sayeram et al.	351/208

FOREIGN PATENT DOCUMENTS

WO	98/08048	2/1998
WO	2006074469	7/2006
WO	WO2007106326	9/2007
WO	2007/130411	11/2007

OTHER PUBLICATIONS

Arimoto et al., "Imaging Properties of Axicon in a Scanning Optical System," Nov. 1, 1992, *Applied Optics*, 31(31): 6652-6657, 5 pages.

Birngruber et al., "In-Vivo Imaging of the Development of Linear and Non-Linear Retinal Laser Effects Using Optical Coherence Tomography in Correlation with Histopathological Findings," 1995, *Proc. SPIE* 2391:21-27, 7 pages.

Chinn, S.R., et al., "Optical coherence tomography using a frequency-tunable optical source," *Optics Letters*, 22(5):340-342, Mar. 1997.

Fercher et al., "Eye-Length Measurement by Interferometry With Partially Coherent Light," Mar. 1988, *Optics Letters*, 13(3):186-188, 3 pages.

Fercher et al., "Measurement of Intraocular Distances by Backscattering Spectral Interferometry," May 15, 1995, *Optics Comm.* 117:43-48, 6 pages.

Huber, R., et al., "Three-dimensional and C-mode OCT imaging with a compact, frequency swept laser source at 1300 nm," *Optics Express*, 13(26):10523-10538, Dec. 2005.

International Search Report and Written Opinion dated Mar. 12, 2009 for International Application No. PCT/US2008/075511, filed Sep. 5, 2008 (9 pages).

Izatt et al., "Micron-Resolution Biomedical Imaging With Optical Coherence Tomography," Oct. 1993, *Optics & Photonics News*, pp. 14-19, 6 pages.

Massow, O., et al., "Femtosecond laser microsurgery system controlled by optical coherence tomography," *Proceedings of the SPIE—Commercial and Biomedical Applications of Ultrafast Lasers VIII*, vol. 6881, pp. 688106(1)-688106(6), Mar. 2008, 6 pages.

Massow, O., et al., "Optical coherence tomography controlled femtosecond laser microsurgery system," *Proceedings of the SPIE—Optical Coherence Tomography and Coherence Techniques III*, vol. 6627, pp. 662717(1)-662717(6), Aug. 2007.

Ohmi, M., et al., "In-situ Observation of Tissue Laser Ablation Using Optical Coherence Tomography," *Optical and Quantum Electronics*, 37(13-15):1175-1183, Dec. 2005, 9 pages.

Sarunic, M., et al., "Imaging the Ocular Anterior Segment With Real-Time, Full-Range Fourier-Domain Optical Coherence Tomography," *Archives of Ophthalmology*, 126(4):537-542, Apr. 2008, 6 pages.

Sarunic, M., et al., "Instantaneous complex conjugate resolved spectral domain and swept-source OCT using 3x3 fiber couplers," *Optics Express*, 13(3):957-967, Feb. 2005 11 pages.

Sarunic, M., et al., "Real-time quadrature projection complex conjugate resolved Fourier domain optical coherence tomography," *Optics Letters*, 31(16):2426-2428, Aug. 2006.

Stern et al., "Femtosecond Optical Ranging of Corneal Incision Depth," Jan. 1989, *Investigative Ophthalmology & Visual Science*, 30(1):99-104, 6 pages.

Swanson, et al., "Method and Apparatus for Optical Imaging with Means for Controlling the Longitudinal Range of the Sample," U.S. Appl. No. 90/006,816, filed Oct. 20, 2003.

Tao, Y., et al., "High-speed complex conjugate resolved retinal spectral domain optical coherence tomography using sinusoidal phase modulation," *Optics Letters*, 32(20):2918-2920, Oct. 2007, 3 pages.

Tommaseo, Giovanni, Examiner, European Patent Office, European Patent Application No. 10191057.8, in European Search Report, mailed Mar. 16, 2011, 3 pages.

Wojtkowski et al., "In Vivo Human Retinal Imaging by Fourier Domain Optical Coherence Tomography," Jul. 2002, *Journal of Biomedical Optics* 7(3):457-463, 7 pages.

Yun, S.H., et al., "Wavelength-swept fiber laser with frequency shifted feedback and resonantly swept intra-cavity acoustooptic tunable filter," *IEEE Journal of Selected Topics in Quantum Electronics*, 3(4):1087-1096, Aug. 1997.

PCT International Search Report and Written Opinion dated Feb. 9, 2012 for International Application Serial No. PCT/US2011/040223.

Kim, Tae Hoon, Authorized Officer, Korean Intellectual Property Office, PCT International Application No. PCT/US2011/025332, in International Search Report, mailed Sep. 16, 2011, 8 pages.

Kim, Tae Hoon, Authorized Officer, Korean Intellectual Property Office, PCT International Application No. PCT/US2011/023710, in International Search Report, mailed Aug. 24, 2011, 8 pages.

Partial International Search Report corresponding to PCT Application Serial No. PCT/US2012/035927 dated Aug. 3, 2012.

Hee, M., et al., "Femtosecond Transillumination Optical Coherence Tomography," *Optics Letters*, Jun. 1993, pp. 950-952, 18(12).

PCT International Search Report and Written Opinion dated Apr. 10, 2012 for International Application No. PCT/US2011/051466, filed Sep. 13, 2011.

* cited by examiner

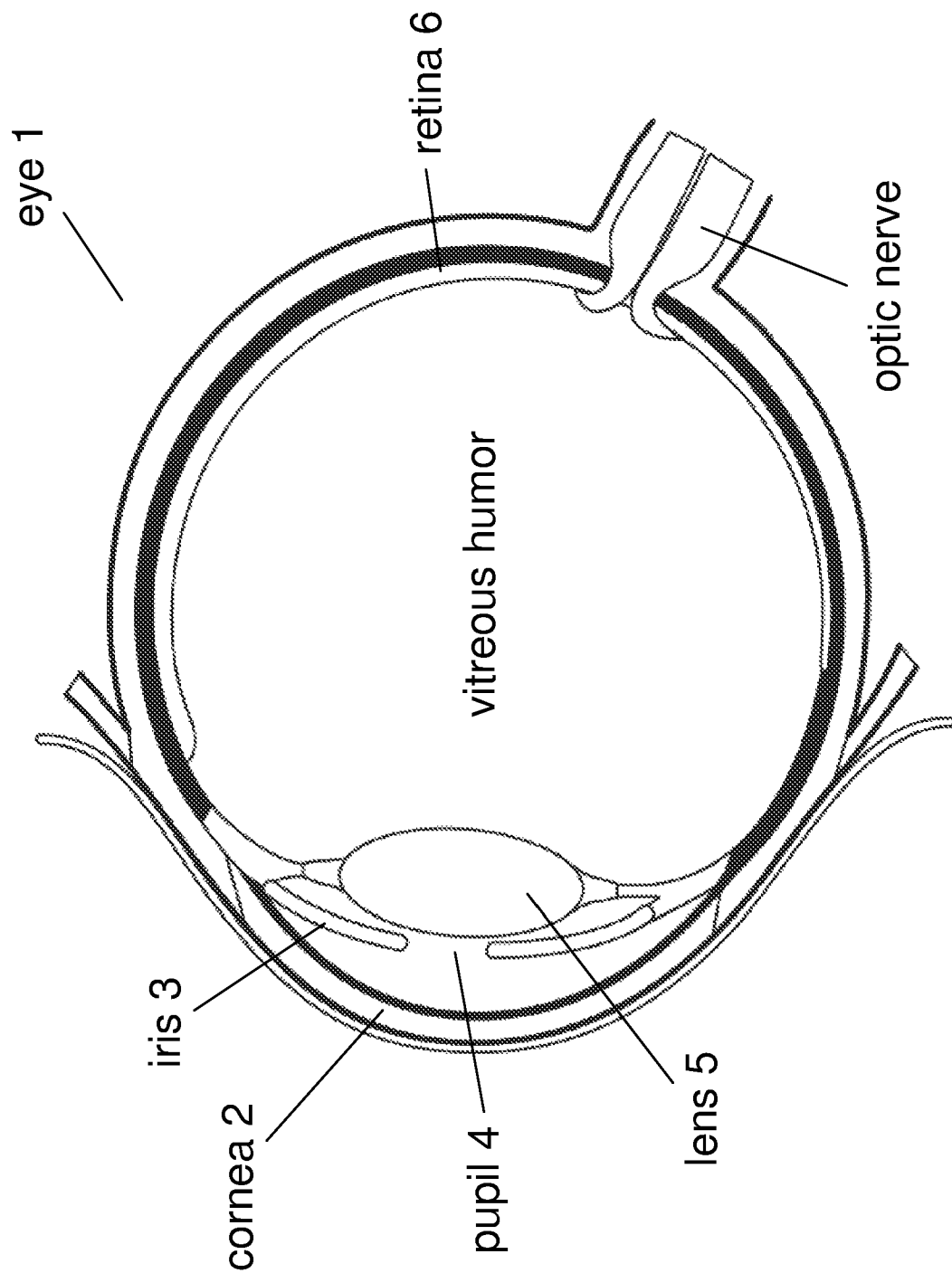


FIG. 1

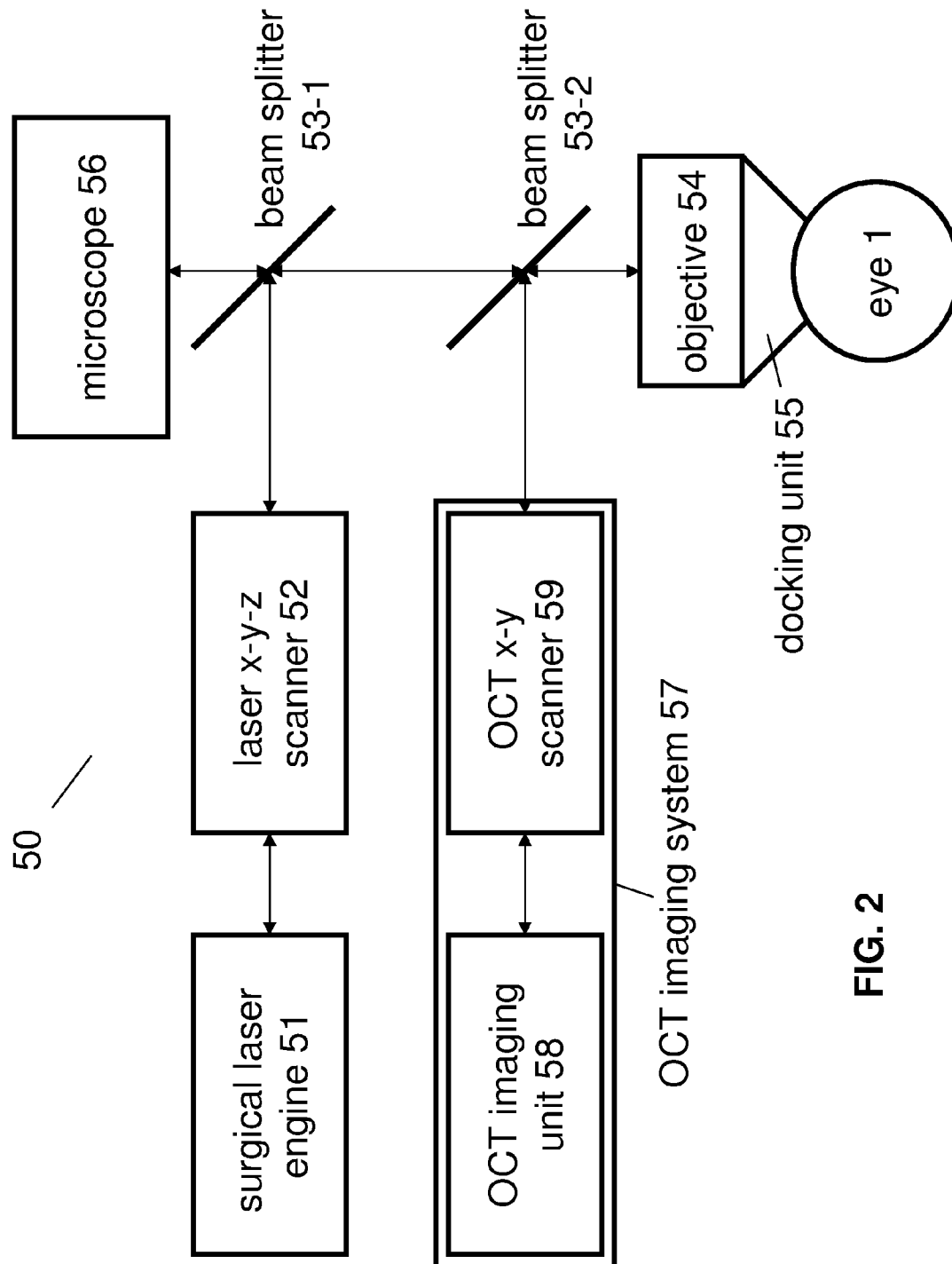
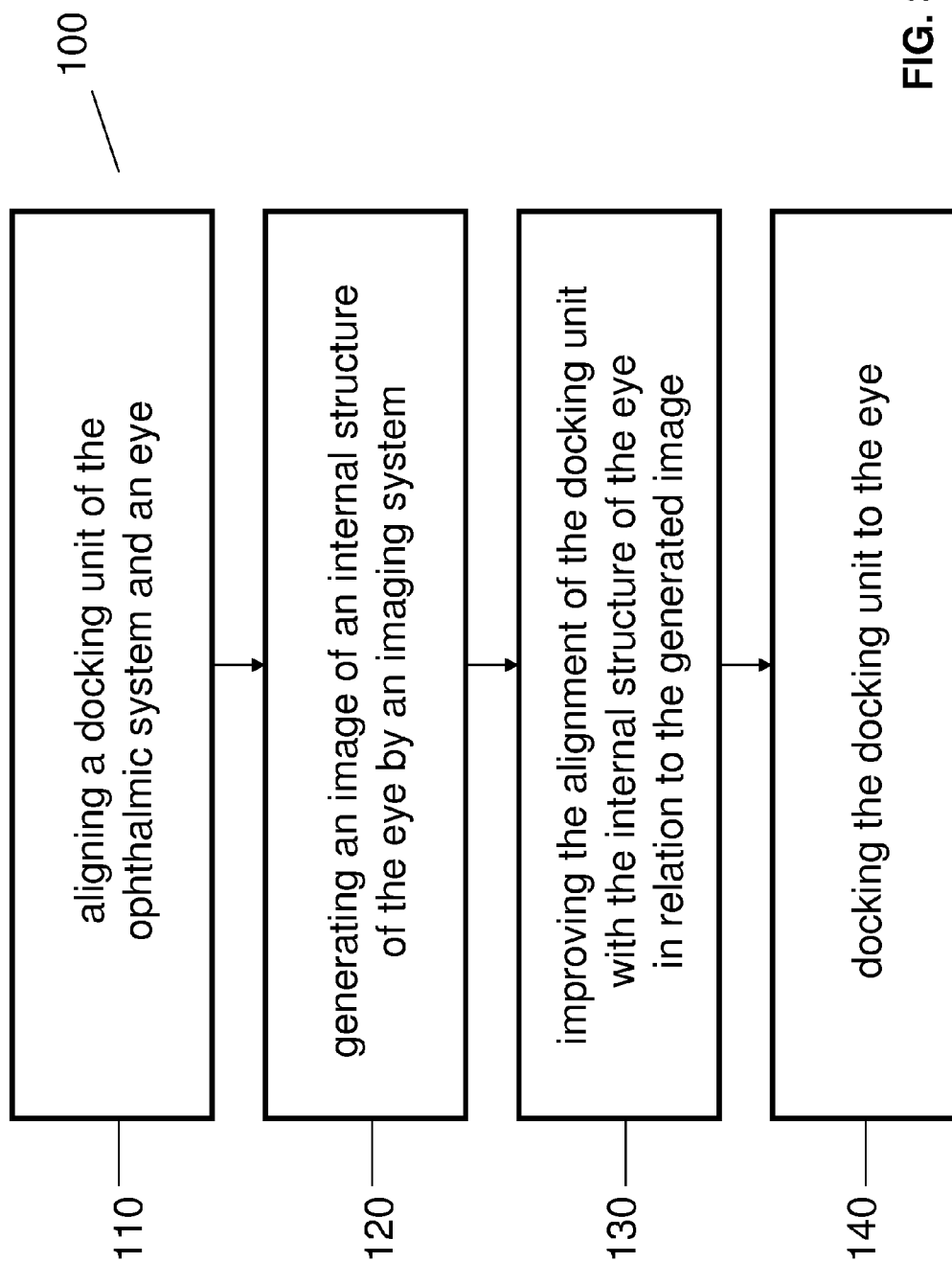


FIG. 2

**FIG. 3**

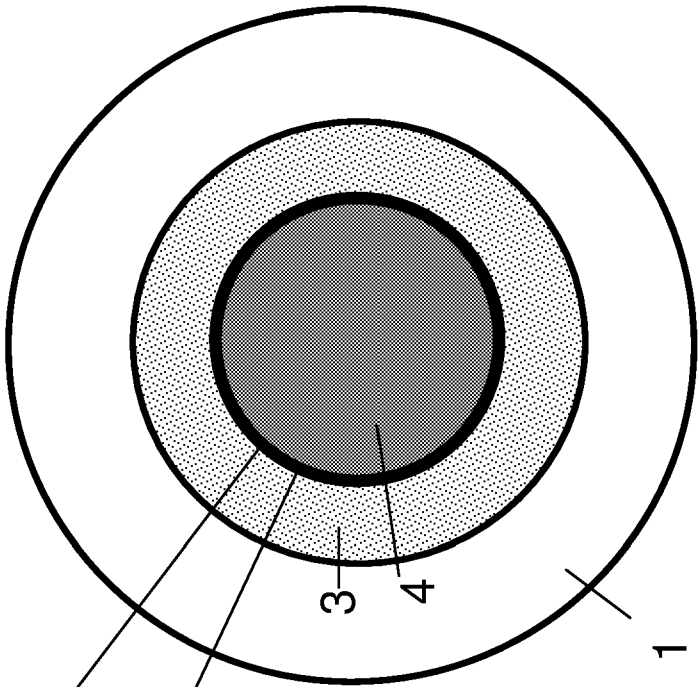


FIG. 4B

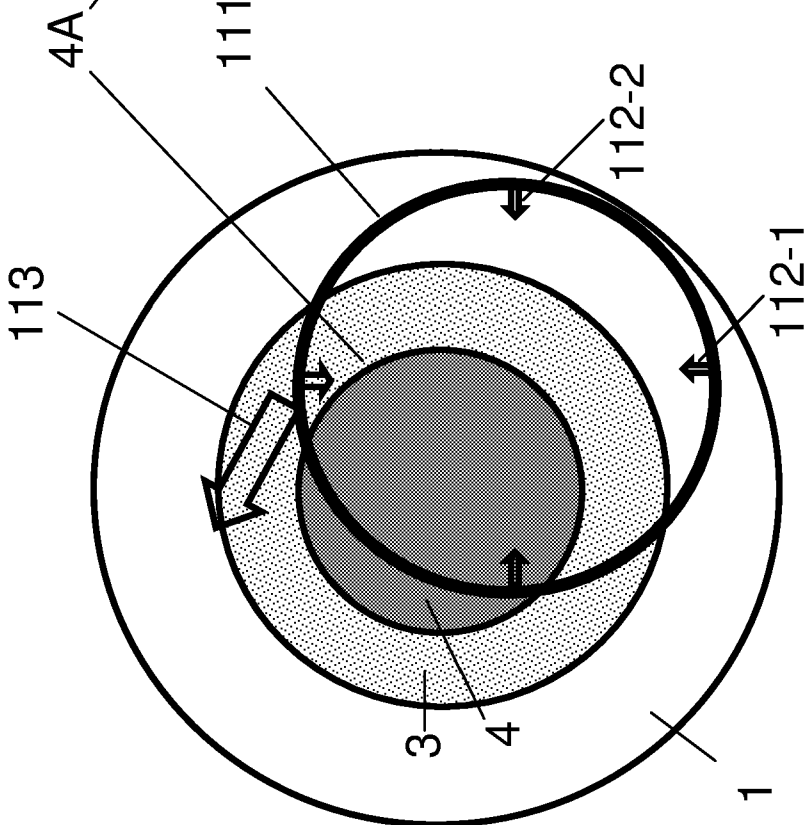


FIG. 4A

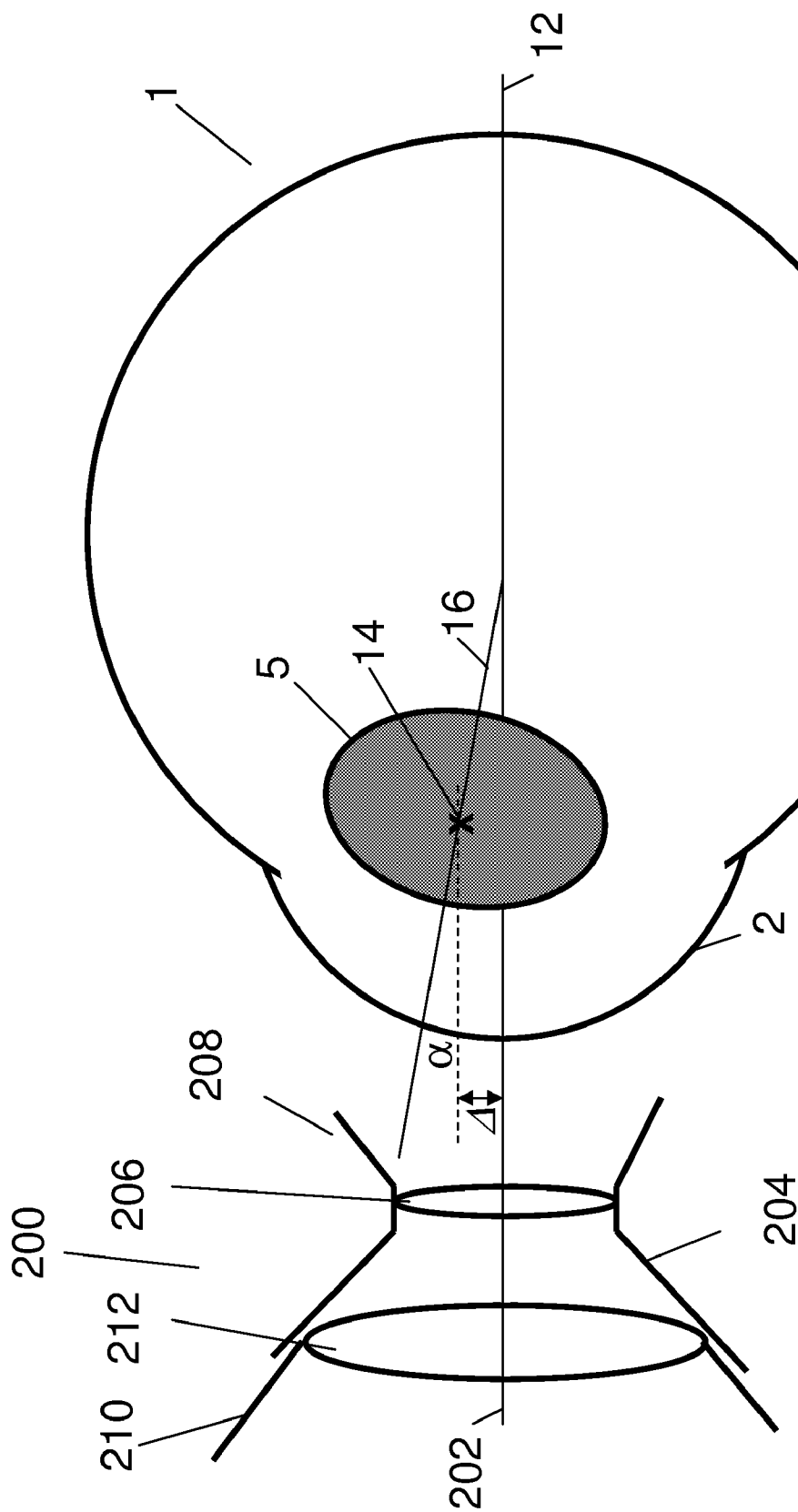


FIG. 5

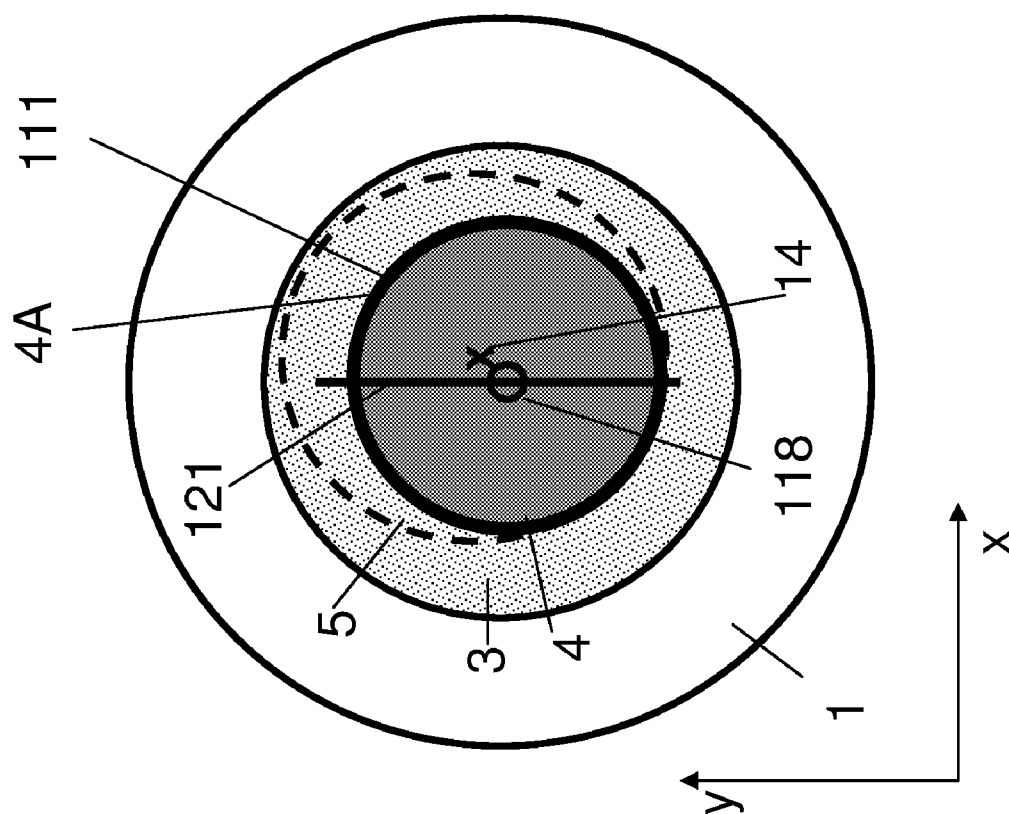


FIG. 6A

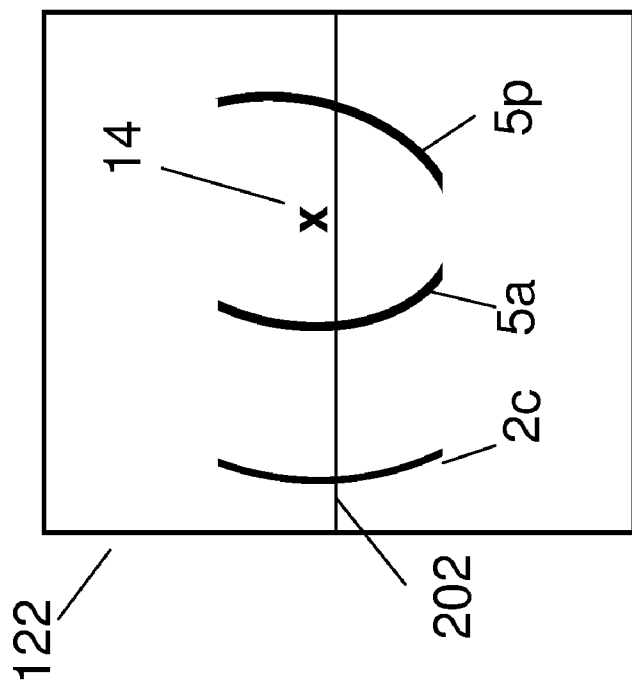


FIG. 6B

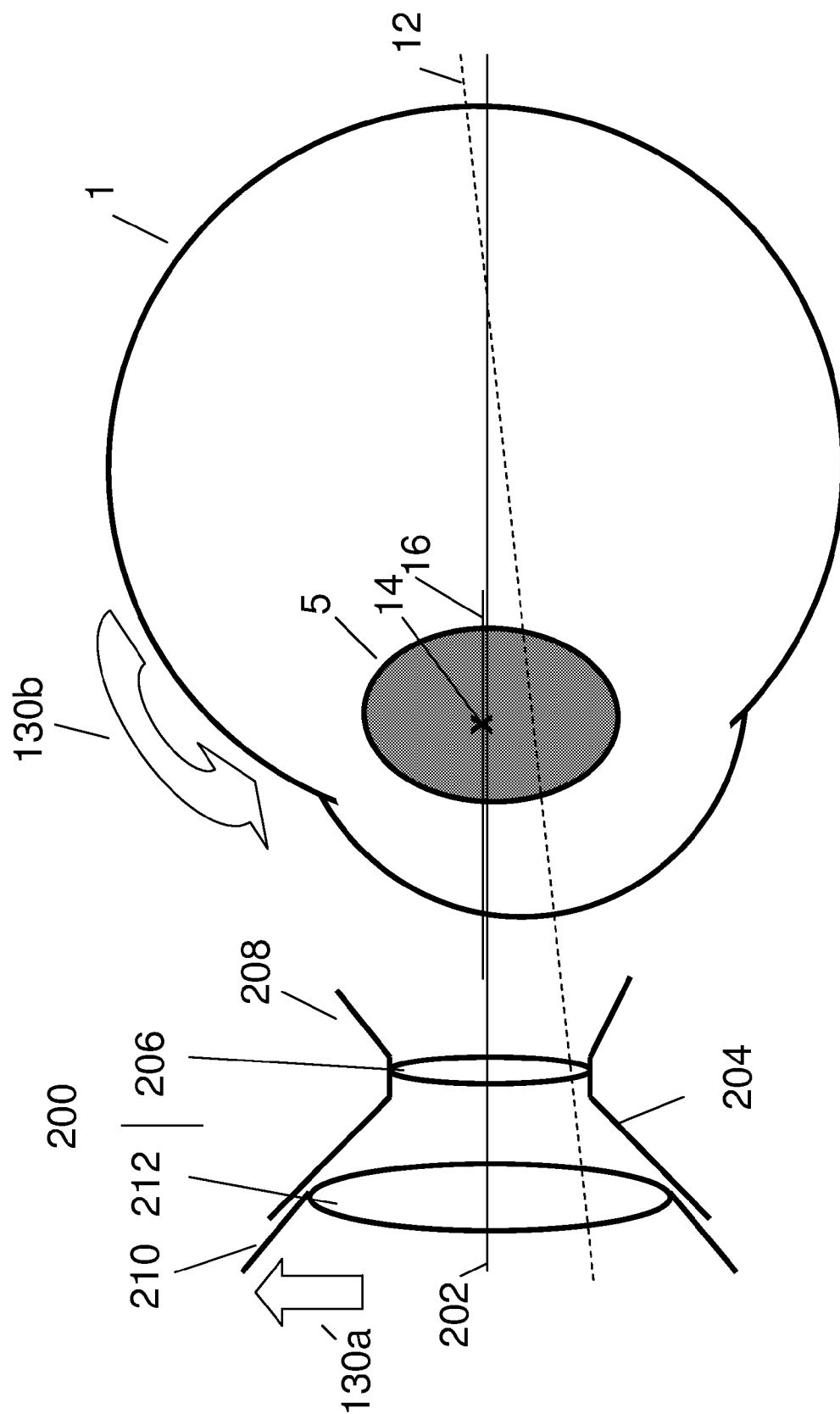


FIG. 7

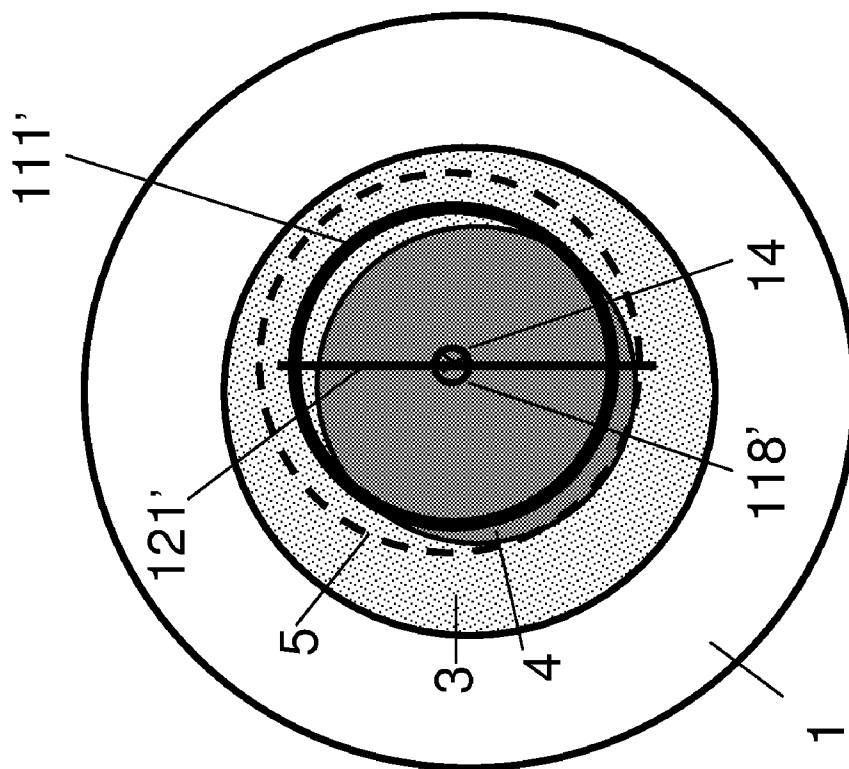


FIG. 8A

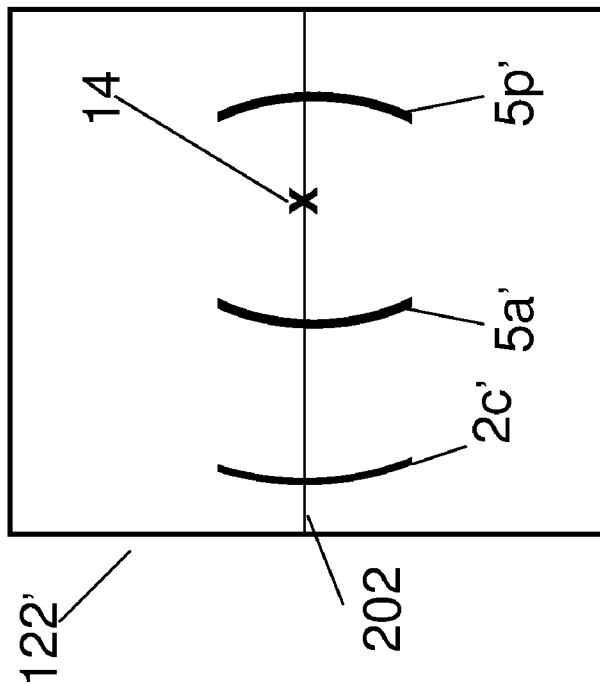
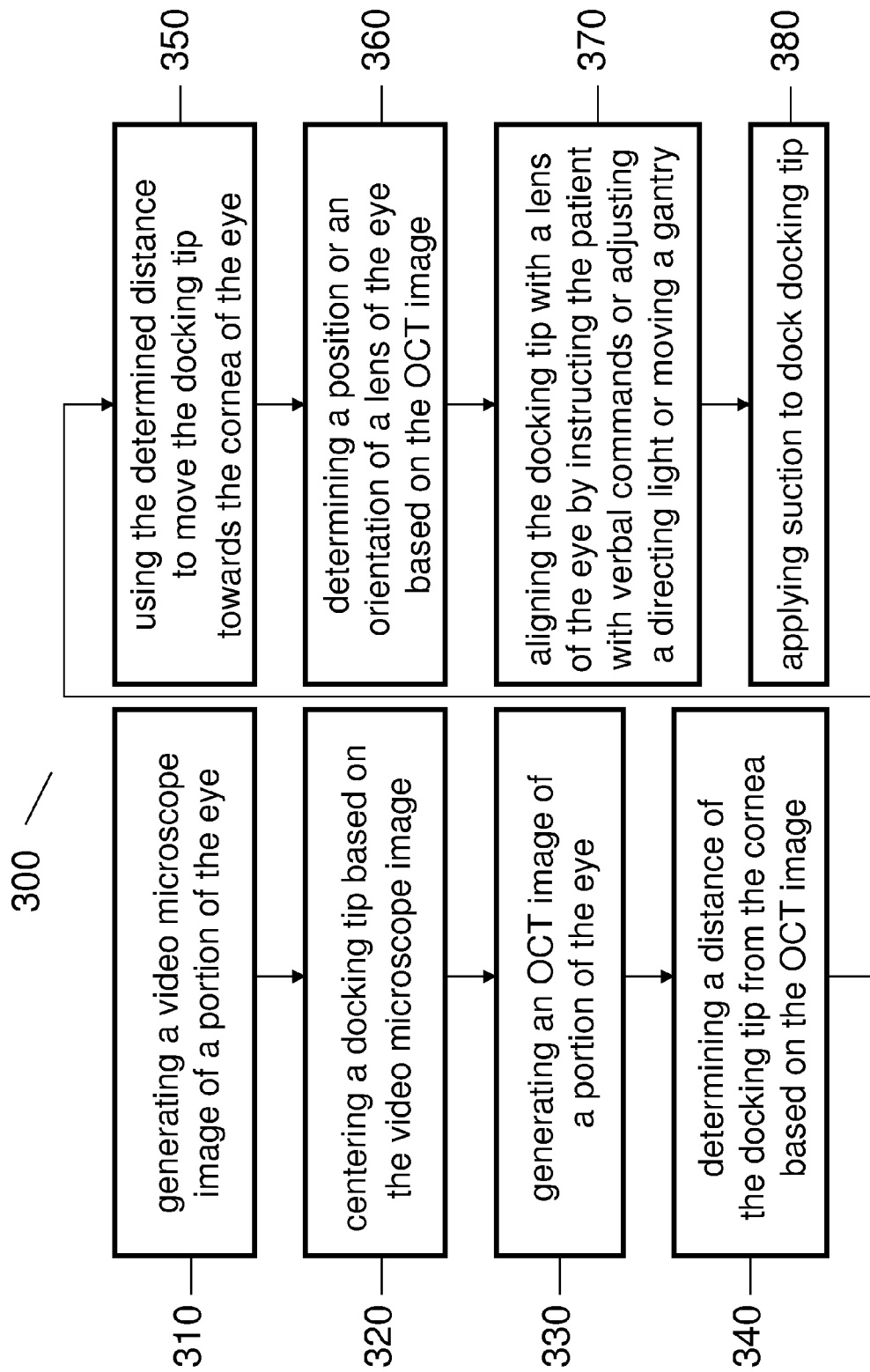


FIG. 8B

**FIG. 9**

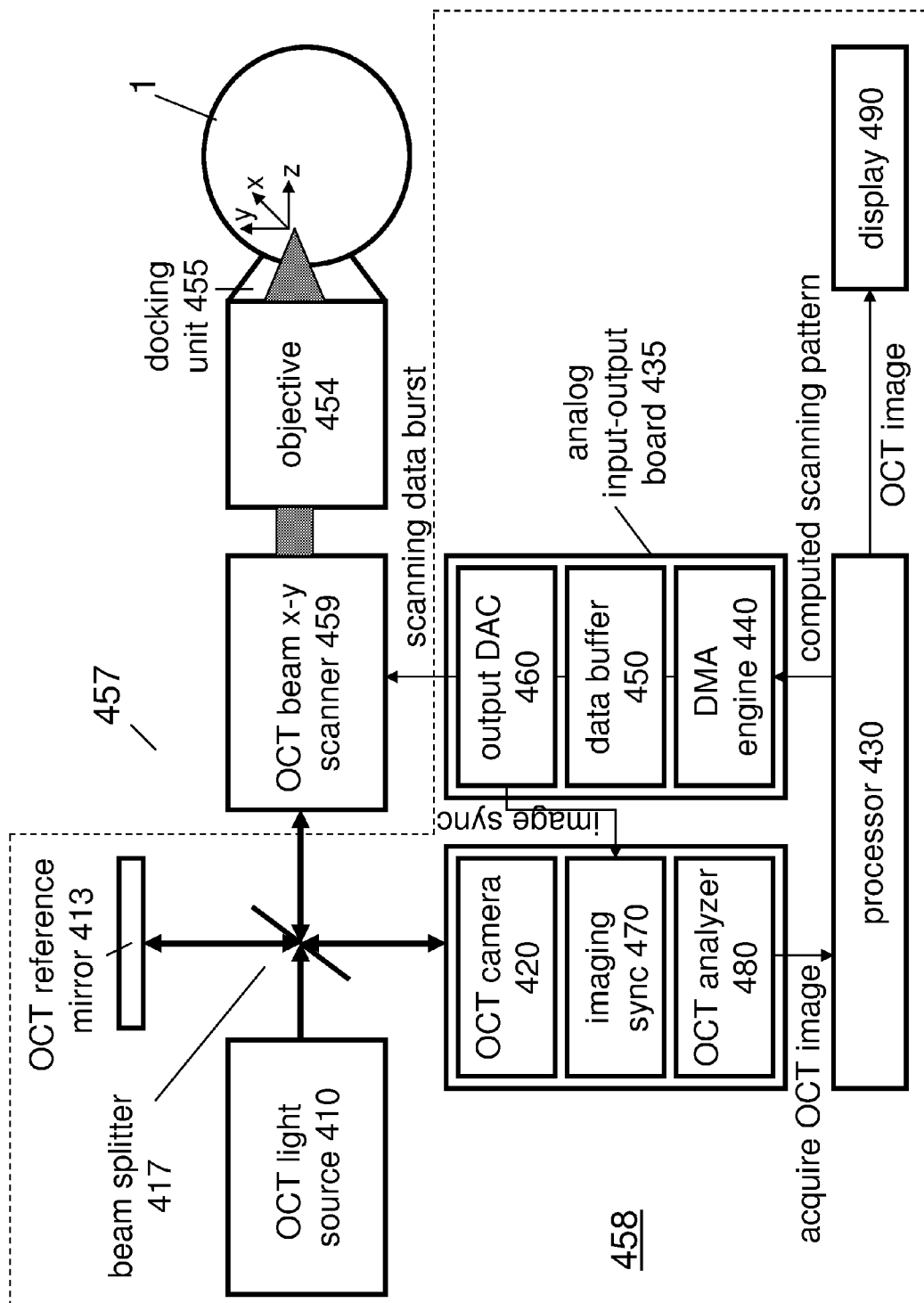


FIG. 10

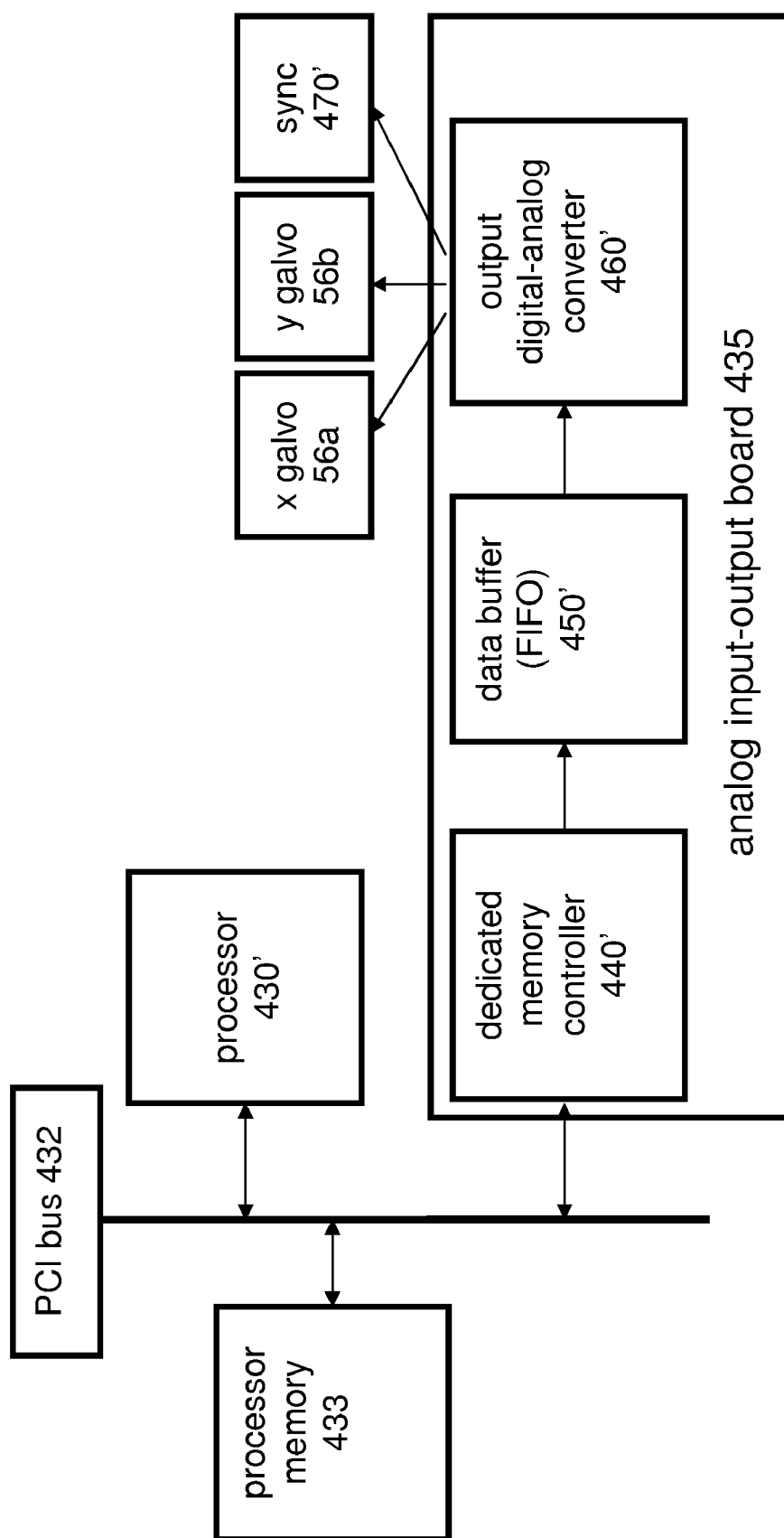
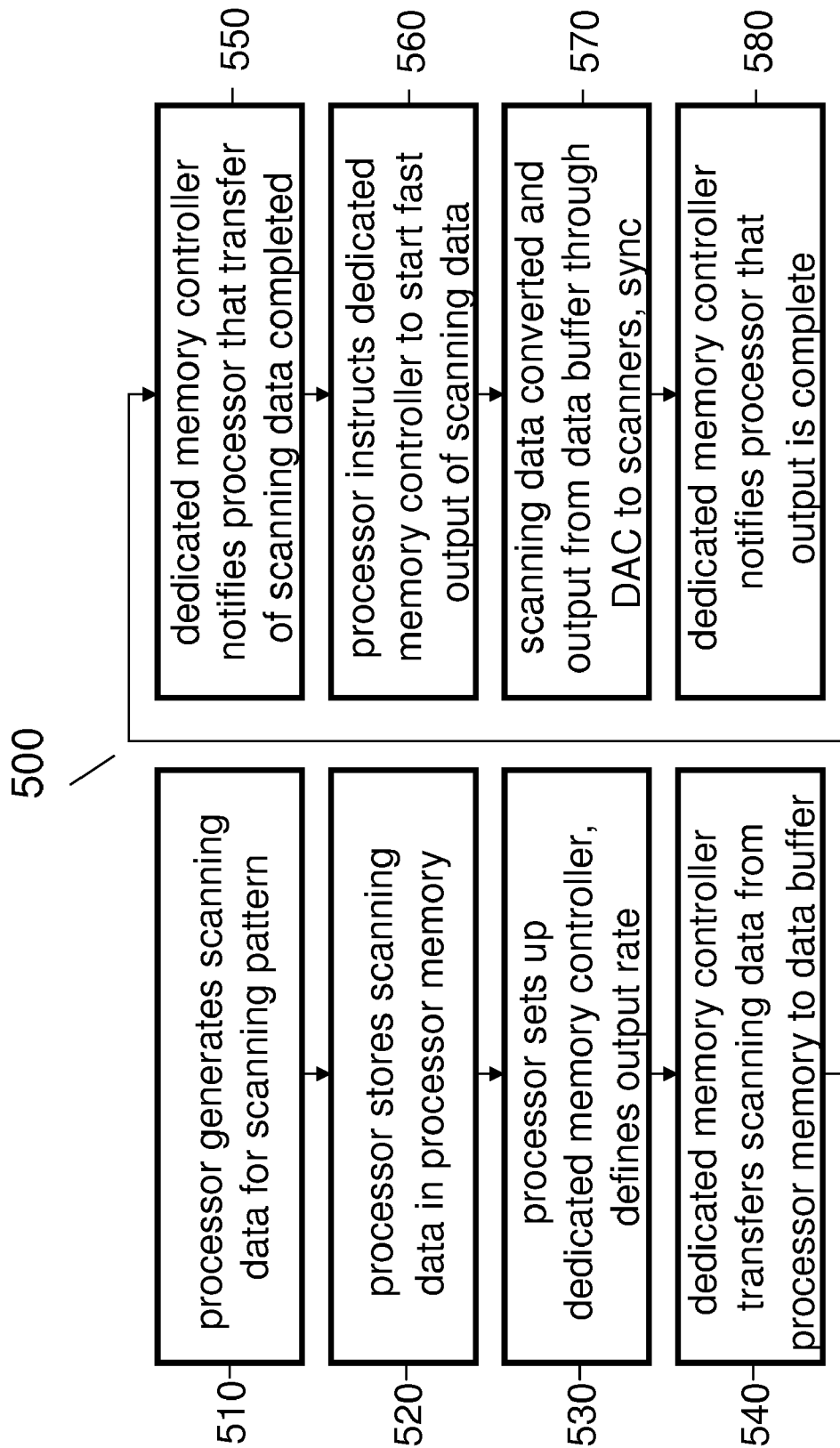


FIG. 11

**FIG. 12**

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IMAGE-GUIDED DOCKING FOR OPHTHALMIC SURGICAL SYSTEMS

TECHNICAL FIELD

This patent document relates to systems and techniques for surgical applications, including ophthalmic surgery. In more detail, the patent document relates to systems and methods for docking ophthalmic surgical systems to a surgical eye with high precision.

BACKGROUND

A variety of advanced surgical laser systems have been developed over the years for ophthalmic surgery, targeting portions of the cornea, the lens, the retina and other structures of the eye. Some of these surgical systems increase the precision of the surgical procedure by creating a well-controlled connection between the ophthalmic surgical apparatus and the ophthalmic target, typically a region or a structure of the eye. In some cases this connection is established by lowering a docking module or unit onto the eye. Certain systems also employ an additional fixation step, such as the application of suction to strengthen the connection. In typical surgical laser systems the precision and control of the ophthalmic surgery is substantially impacted by the precision of these docking and fixation steps and hence improving the precision of the docking procedure can improve the precision of the entire ophthalmic surgical procedure.

SUMMARY

This patent document discloses examples and implementations of systems and techniques for guiding an ophthalmic surgical system to create a well-controlled connection with an ophthalmic target, such as a human eye.

For example, a docking method for an ophthalmic system may include the steps of aligning a docking unit of the ophthalmic system and an eye; generating an image of an internal structure of the eye by an imaging system; improving an alignment of the docking unit with the internal structure of the eye in relation to the generated image; and docking the docking unit to the eye.

The aligning the docking unit step may include using a first imaging system to align a target pattern of the ophthalmic system in relation to a feature of the eye.

The first imaging system can be one of a microscope or a video microscope; the target pattern of the ophthalmic system can include at least one of a center of a contact lens, a center of the docking unit, a docking circle, or a docking cross-hair; and the feature of the eye may be a center of a region of an iris, a pupil, a cornea, a limbus, or a lens; or a circular formation related to a region of the iris, the pupil, the cornea, the limbus or the lens.

The generating an image step may include generating an image with a second imaging system, wherein the second imaging system is one of an optical coherence tomographic imaging system and an imaging system configured to image the internal structure of the eye.

The improving an alignment step may include extracting position information regarding the internal structure of the eye from the generated image; and adjusting a position of at least one of the eye or the docking unit in relation to the extracted position information.

The improving an alignment step may include extracting orientation information regarding the internal structure of the eye from the generated image; and adjusting an orientation of

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at least one of the eye or the docking unit in relation to the extracted orientation information.

The generating the image step may include computing scanning data by a processor corresponding to a scanning pattern; storing the scanning data in a data buffer; transferring the scanning data by the data buffer to an output module; outputting scanning signals by the output module to one or more scanners based on the scanning data; and scanning an imaging beam with the one or more scanners according to the scanning signals.

The computing the scanning data step may include implementing a scanning pattern that includes at least one of a linear pattern, a circular pattern, an oval pattern, a loop pattern, an arc pattern, a raster pattern, an x-y pattern, a crosshair pattern, a star pattern, a spiral pattern, and a pattern with outlying points.

The computing the scanning data step may include inserting synchronizing signals into the scanning data by the processor.

The computing the scanning data step may include computing homing data corresponding to a homing pattern connecting a starting point of the scanning pattern to a previously set point.

The storing the scanning data step may include storing the scanning data in a processor memory; and transferring the stored scanning data from the processor memory to the data buffer partially under the control of a dedicated memory controller.

The dedicated memory controller may include a direct memory access engine; and the data buffer may include a first-in-first-out memory.

The transferring the scanning data step may include outputting the scanning data by the data buffer to the output module in a fast data transfer mode.

The transferring the scanning data step may include outputting the scanning data from the data buffer without sending the scanning data through at least one of a bus connecting the dedicated memory controller and the processor, the processor memory, or the processor.

The transferring the scanning data step may include outputting the scanning data in parallel with the processor performing at least one of processing an image, computing scanning data corresponding to a scanning pattern, or performing a control function.

The transferring the scanning data step may include receiving the scanning data by the output module without an interrupt by another system agent, thereby keeping a jitter of the scanning data below 40 microseconds.

The outputting the scanning signals step may include converting the scanning data into analog scanning signals by the output module, wherein the output module includes a digital-analog converter.

The scanning an imaging beam step may include receiving the outputted scanning signals by a scanning controller and an imaging synchronizer, wherein the scanning signals comprise synchronizing signals; repeatedly adjusting the one or more scanners by the scanning controller according to the scanning signals to scan the imaging beam; and repeatedly synchronizing an imaging camera by the imaging synchronizer according to the synchronizing signals.

The scanning controller may include at least one galvo-controller; and the imaging synchronizer may include at least one ophthalmic coherence imaging camera controller.

In some implementations an integration time of an image recording device can be a limiting factor of an operating speed of an imaging system.

The outputting the scanning signals step may include outputting the scanning signals at a rate within one of the following ranges: 1 Hz-1 MHz, 100 Hz-1 MHz, or 1 kHz-100 kHz.

The outputting the scanning signals step may include adjusting an output rate of the output of the scanning signals.

The improving the alignment step may include providing a verbal command to a patient to move his eye, moving the patient's head, moving a surgical bed the patient is resting on, moving the patient's eye, moving the docking unit via moving a gantry or an articulated arm, and using a gripper to move the eye, based on the image of the internal structure of the eye.

The improving the alignment step may include adjusting at least one of a fixation beam or a directing light to improve the alignment of the eye and the docking unit; and directing the patient to follow the fixation beam or the directing light with his eye.

The improving the alignment step may include starting the improving the alignment step before the docking unit makes contact with the eye, after the docking unit makes contact with the eye but before an application of a partial vacuum to the docking unit, or after an application of a partial vacuum.

The docking step may include sensing a distance between a reference point of the docking unit and an outer layer of the eye; and lowering the docking unit according to the sensed distance.

In some implementations the reference point can be adjustable.

The docking step may include bringing the docking unit into physical contact with the eye; and applying suction through a portion of the docking unit after the docking unit makes physical contact with the eye.

In some implementations an imaging controller for an ophthalmic system may include a processor that computes scanning data for a scanning pattern; a local memory controller that partially manages a transfer of the computed scanning data from the processor to a data buffer, wherein the data buffer is configured to store the scanning data and to output the scanning data; and an output digital-analog converter, coupled to the data buffer that converts selected scanning data to analog scanning signals and outputs the scanning signals.

The local memory controller may include a direct memory access engine.

The data buffer may include a first-in-first-out memory that outputs the stored scanning data in a fast data transfer mode.

The imaging controller may further include a processor memory; and a bus, coupled to the processor, the local memory controller and the processor memory, wherein the processor is configured to output the computed scanning data to the processor memory through the bus; and the local memory controller is configured to transfer the scanning data from the processor memory to the data buffer through the bus.

In some implementations the data buffer is configured to output the scanning data without sending the scanning data through at least one of the bus, the processor memory, or the processor.

In some implementations the processor is configured to perform at least one of processing an image and computing scanning data, while the data buffer outputs the scanning data.

In some implementations the output digital-analog converter is coupled to the data buffer so that the scanning data, outputted by the data buffer is received without an interrupt by another system agent, thereby keeping a jitter of the scanning data below 40 microseconds.

In some implementations the output digital-analog converter is configured to output the scanning signals to x and y scanning controllers to scan an imaging beam; and synchro-

nizing signals to an imaging camera to record a returned imaging beam synchronously with the scanning.

In some implementations a method of controlling an ophthalmic imaging may include computing scanning control data by a processor; storing the scanning control data into a data buffer partially under the control of a memory controller; transferring the scanning control data from the data buffer to a signal converter through a dedicated channel; and sending scanning signals to a scanning controller by an output module, wherein the scanning signals are converted from the scanning control data by the signal converter.

The storing the scanning control data step may include storing the computed scanning control data in a processor memory; and moving the scanning control data from the processor memory to the data buffer.

The transferring the scanning control data step may include transferring the scanning data from the data buffer without sending the scanning data through at least one of a bus connecting the local memory controller and the processor, the processor memory, or the processor.

The transferring the scanning control data step may include transferring the scanning data in parallel with the processor performing at least one of processing an image; and computing scanning data corresponding to a scanning pattern.

The transferring the scanning control data step may include transferring the scanning data without an interrupt by another system agent, thereby keeping a jitter of the scanning data below 40 microseconds.

The local memory controller may include a direct memory access engine; and the data buffer may be a first-in-first-out memory.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 illustrates the human eye.

FIG. 2 illustrates an ophthalmic surgical system.

FIG. 3 illustrates a docking method.

FIGS. 4A-B illustrate an aligning step.

FIG. 5 illustrates the tilt and displacement of a lens relative to the docking unit.

FIGS. 6A-B illustrate a tilted and displaced lens and its image.

FIG. 7 illustrates an improvement of the alignment between the lens and the docking unit.

FIGS. 8A-B illustrate the alignment of the docking unit with the lens after the alignment-improving step, and the corresponding image.

FIG. 9 illustrates a docking method guided by an imaging method.

FIG. 10 illustrates an image-guided docking system.

FIG. 11 illustrates blocks of the image-guided docking system in detail.

FIG. 12 illustrates the steps of a control method of the image-guided docking method.

DETAILED DESCRIPTION

Many ophthalmic surgical systems include a docking unit, or patient interface, that makes contact with a surgical eye and keeps it effectively immobile relative to an objective of the surgical system during an ophthalmic procedure. The precision of the ophthalmic procedure can be increased by increasing the precision of the alignment of the docking unit with the target of the surgery.

In corneal procedures, where the surgical target—the cornea—is unobstructed and visible, aligning the patient inter-

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face with the target can be performed by the surgeon in a relatively straightforward manner.

However, cataract surgeries pose harder challenges for the alignment and docking of the patient interface for several reasons. These challenges include that the targeted lens is located inside the eye and thus it is less visible for, or partially obstructed from the surgeon.

Also, patients often have difficulties aligning their surgical eye with the optical axis of the ophthalmic surgical system even if given guidance and verbal instructions by the surgeon, as e.g. often the patients are given muscle relaxants or are under heavy sedation.

Further, internal eye structures, such as the lens, are often held by their soft support muscles off-center and tilted relative to the visible structures of the eye, such as the pupil. Therefore, even if a surgeon manages to align the pupil with the optical axis of the surgical system, the lens inside the eye may be still displaced and tilted.

Moreover, as the docking unit is lowered to the eye, it exerts pressure on the eye, possibly resulting in additional displacement and tilting of the lens. This problem can be exacerbated even further by applying suction to dock the patient interface.

Implementations and embodiments in this patent document provide docking procedures and systems for increasing the precision of the docking procedure of ophthalmic surgeries by imaging techniques.

FIG. 1 illustrates a human eye 1 in some detail. The eye 1 includes a cornea 2 that receives and refracts the incoming light, an iris 3, a pupil 4 that provides an opening for the light to enter the inner eye and a lens 5 that focuses the light on the retina 6. As stated above, the lens 5 is often not aligned with the pupil 2, and its soft supporting ciliary muscle-system can allow additional displacement and tilt when the eye 1 is pressured by the docking unit, exacerbating the problem of misalignment with the docking unit.

Implementations and embodiments in this patent document provide docking procedures and systems for increasing the precision of the docking procedure of ophthalmic surgeries by imaging techniques.

FIG. 2 illustrates an ophthalmic laser surgical system 50. The surgical system 50 can include a surgical laser engine 51 that generates the surgical laser beam. The surgical laser beam can be scanned across the surgical target region by a laser x-y-z scanner 52. The surgical laser beam can be coupled into the main system optical path by a beam splitter 53-1, redirecting it to an objective 54. The objective 54 can be part of or may contain a delivery tip, distal end, or lens cone.

In some implementations, parts of the laser x-y-z scanner 52, such as a z scanner block, can be located after the beam splitter 53-1 in the optical path. The z scanner block can be a separate unit, or may include more than one block, or can be part of the objective 54. Each of the x, y, and z scanners may contain more than one functional unit. For example, multiple minors can be used to perform the scanning in the x direction or the y direction, or multiple and separate lens groups can be used for an optimized z scanning.

A docking unit 55 can be removably appended to the objective 54 to make contact with the eye 1 to increase the precision of the targeting of the surgical laser beam into the surgical target region in the eye. The docking unit may be integrated into one piece or may contain more than one piece. A first part of a multi-piece docking unit can be first attached to the surgical eye, whereas a second part of the docking unit can be first attached to the objective 54, or a delivery tip. Subsequently, the first and second parts of the docking unit can be locked together. The docking unit 55 may be referred to as a patient interface, application tip, docking tip, lens cone, or

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applanation device, and may contain a contact lens or applanation lens which may make a contact with the eye or can be disposed close to the eye.

The surgical and docking procedures can be assisted by various imaging systems. In some surgical systems 50, a first imaging system, such as an ophthalmic surgical stereo microscope or video microscope 56, can be provided to image the surgical target region for the surgeon. The (ophthalmic or video) microscope 56 may make use of an observational or imaging light.

The imaging light may share part of the main optical path of the surgical system 50, or can be projected directly to the target region. In a shared-path implementation, the observational light can be generated close to the microscope 56, subsequently guided to the eye and returned from the eye, entering the main optical path or optical train of the surgical system 50 through the beam splitter 53-1. In a non-shared-path implementation, the imaging light can be generated close to and outside the objective 54 and directly projected onto portions of the eye. In this embodiment only the returned portion of the imaging light may be guided through the main optical pathway of the system to the microscope 56.

Some implementations may include a second imaging system in the surgical system 50 to provide imaging data about the inner structures of the eye and the target region. Using the images from the first and second imaging systems in synergy can provide enhanced guidance for the ophthalmic procedure in general and improve the accuracy of the docking of the patient interface in particular.

In some surgical systems 50 the second imaging system can be an optical coherence tomography (OCT) imaging system 57. The OCT imaging system 57 can be a time-domain, a swept-source or a spectrometer based OCT imaging system, among others. The OCT imaging system 57 can include an OCT imaging unit 58 that creates an OCT imaging beam, guides the OCT imaging beam toward the eye and processes the OCT imaging beam returned from the eye. The OCT imaging system 57 can also include an OCT x-y scanner 59 that scans the OCT imaging beam across the target region in the x-y plane which can be e.g. perpendicular to the optical axis.

In general, the notation "x-y-z" is used in a broad sense throughout this document: it can refer to scanning in three directions which make substantial angles with each other. These angles, however, may not be necessarily right angles. Also, the scanning may be performed along either straight or curved lines, on flat or curved surfaces in a grid, raster, concentric, spiral, or any other pattern. In some implementations the OCT imaging beam may be scanned by the surgical laser x-y-z scanner 52. In others, only some of the scanning functionalities of the surgical laser beam and the OCT imaging beam are performed by a shared scanner block, such as the x-y scanning functionality. Some OCT systems, such as time domain OCT systems require a z scanning of the beam, whereas others, such as spectrometer based OCT systems, do not require z scanning as they capture image data from all depth at essentially the same time.

The OCT imaging beam can be coupled into the main optical path of the surgical system 50 through a beam splitter 53-2, and directed into the target region by the objective 54 and docking unit 55. In some implementations, part or all of the z scanning functionality can be performed by a z scanner disposed in the shared optical path, after the beam splitter 53-2. The z scanner can be even part of the objective 54.

FIG. 3 illustrates a docking method 100 for the ophthalmic laser surgical system 50, where the docking method 100 may include:

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An aligning step **110** for aligning the docking unit **55** of the ophthalmic system **50** and the eye;

An imaging step **120** for generating an image of an internal structure of the eye by an imaging system;

An alignment-improving step **130** for improving the alignment of the docking unit **55** with the internal structure of the eye in relation to the generated image; and

A docking step **140** for docking the docking unit **55** to the eye.

These steps are described in detail below.

The aligning step **110** may include using the first imaging system to align a target pattern of the ophthalmic laser surgical system **50** with a feature of the eye. This aligning step **110** can be performed e.g. in relation to lowering the docking unit **55** towards the eye. The first imaging system may be the ophthalmic surgical microscope or video microscope **56**.

The target pattern of the ophthalmic laser surgical system **50** can include at least one of a mark of a center of a contact lens, of a center of the docking unit **55**, or of an optical axis of the objective **54**, the docking unit **55** or the contact lens. In other implementations, it can include a docking circle, a docking cross-hair, or any other docking target pattern, as well as a combination of the above patterns. This target pattern can be formed in the optics of an ophthalmic surgical microscope **56**, or can be electronically generated and displayed on a display or screen of a video microscope **56**.

The feature of the eye can be a center of a region of the cornea **2**, the iris **3**, the pupil **4**, a limbus, a sclera, or the lens **5**; or a circular formation related to a region of the cornea **2**, the iris **3**, the pupil **4**, the limbus, the sclera, or the lens **5**.

FIGS. 4A-B show an illustrative example of the aligning step **110**. In FIG. 4A, the video microscope **56** displays the eye **1** as seen through the objective **54** of the laser surgical system **50**, and a variable radius target pattern circle **111**, centered at the shared optical axis of the objective **54** and docking unit **55**. As the surgeon lowers the docking unit **55** towards the eye, in a pattern adjusting step **112** he may adjust the variable radius of the target pattern circle **111** to be essentially equal to the radius of the inner circular edge **4A** of the patient's pupil **4**, as indicated by the arrows **112-1** and **112-2**. In addition, in a pattern moving step **113**, the surgeon may also adjust or move the docking unit **55** in the x-y plane, as shown by the arrow **113**, to align the target pattern circle **111** with the inner circular edge **4A** of the pupil **4** before, during or after the radius adjustment.

The radius of the target pattern circle **111** can be chosen to be somewhat different from the radius of the inner circular edge **4A** of the pupil **4** as long as the radius enables the surgeon to align the target pattern circle **111** with the pupil **4** with a desired precision. In other embodiments, any other target pattern can be used, including arcs, cross-hairs, and raster patterns, as listed above.

FIG. 4B illustrates that the adjusting of the variable radius of the target pattern circle **111** in step **112** and the moving of the docking unit **55** in the x-y plane in step **113** may be repeatedly and iteratively performed until the target pattern circle **111** essentially coincides with the inner circular edge **4A** of the pupil **4**. Doing so aligns the shared optical axis of the objective **54** and the docking unit **55** with the axis or center of the pupil **4**.

During this aligning step **110** the docking unit **55** may get lowered toward the eye, possibly even getting into physical contact with the eye during an adjustment of the z directional position of the docking unit **55**. However, in either case the docking unit **55** still can remain movable relative to the eye, allowing the surgeon to carry out the aligning step **110**, possibly iteratively. Even at the end of aligning step **110** the

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docking unit may remain movably connected to the eye to allow for a possible subsequent aligning step.

In some implementations, the aligning step **110** may not involve a target pattern. In these cases the alignment of the docking unit **55** may be guided primarily by the visual assessment of the surgeon.

Embodiments of this aligning step **110** align the docking unit **55** and the eye to a certain precision. If the docking unit is docked to the eye after aligning step **110**, an ophthalmic procedure can be performed with a certain precision. For some procedures this precision may be sufficient, but others may benefit from a higher precision.

FIG. 5 illustrates such a situation. Even after an optical axis **202** of a docking unit **200** is aligned with the pupil **4** of the eye in the aligning step **110**, the lens **5** of the eye may remain displaced and tilted relative to the optical axis **202**, as the lens **5** may not be aligned with the pupil **4** for one of the reasons outlined above. Here, the docking unit **200** can be an embodiment of the docking unit **55**.

In FIG. 5, even after an optical axis **12** of the pupil **4** and the eye has been aligned with the optical axis **202** of the docking unit **200** in the aligning step **110**, a center **14** of the lens **5** is still offset by Δ from the shared optical axis **12/202** of the pupil **4** and the docking unit **200**, and a symmetry axis **16** of the lens **5** still makes an angle α with the shared optical axis **12/202**.

Here, the body or housing **204** of the docking unit **200**, sometimes called patient interface, lens cone, or application tip, may contain a contact lens, applanation lens or applanation plate **206** and a skirt or flexible seal **208**, which makes contact with the outer eye-surface, typically with the cornea, limbus, or sclera. The docking unit **200** can be affixed to an embodiment of the objective, delivery tip, or distal end **210** or **54**, which may include several lenses, the ultimate lens being distal lens **212**.

FIGS. 6A-B illustrate the imaging step **120** in some detail.

FIG. 6A illustrates that in the aligning step **110** the docking unit **55** or **200** can be properly aligned and centered with the pupil **4** using the video microscope **56**, as evidenced by the target pattern circle **111** overlapping with the inner circular edge **4A** of the pupil **4**, and its center **118** (denoted by a circle) being at the center of the pupil **4**. However, the lens **5**, shown with a dotted line as its outer perimeter is hidden from the view of the video microscope **56**, can be off-center with respect to the pupil **4**. This is indicated also by the center **14** of the lens, denoted by an x, being off the center **118** of the target pattern **111**, denoted by the circle. Furthermore, the axis **16** of the lens **5** can be tilted relative to the shared axis **202/12** of the docking unit **200** and pupil **4**.

Therefore, even after the aligning step **110**, the target pattern circle **111** may not be well-aligned with the lens **5**, and thus the precision of cataract procedures centered with the target pattern circle **111** may not be optimal. This non-optimal precision can be improved by performing the imaging step **120**.

FIGS. 6A and B illustrate that in a typical case, the imaging step **120** can include a linear scan **121** across the center **118** of the target pattern circle **111** which coincides with the center of the pupil **4**. This linear scan **121** generates a y-z image **122** that includes an image **2c** of a corneal segment and images **5a** and **5p** of segments of the anterior and posterior lens capsule, respectively. The images of the lens segments **5a** and **5p** appear tilted and off center relative to the optical axis **202** in the y-z image **122**, even if the corneal segment image **2c** appears centered, since the lens **5** can be tilted and off-center relative to the cornea and pupil. Therefore, providing the

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images of the lens segments **5a** and **5p** may help the surgeon to improve the alignment of the docking unit **200** with the tilted and off-center lens **5**.

In other implementations, the imaging step **120** can involve generating an image with a line scan along a linear pattern, an arc, a crosshair pattern, a star pattern, a circular pattern, an oval pattern, a loop pattern, a spiral pattern, a concentric multi-circle pattern, a shifted multi-circle pattern, a line pattern, and with a two dimensional scan along an x-y, raster or grid scanning pattern and a pattern with outlying points.

The imaging step **120** can involve generating an image with an embodiment of the optical coherence tomographic (OCT) imaging system **57**, as described in detail above and below. The imaging step **120** can be also performed with another imaging system, capable of imaging an internal structure of the eye.

FIG. 7 illustrates that the alignment of the docking unit **200** with the lens **5** can be improved by the alignment-improving step **130**, based on the imaging step **120**.

In one aspect, the alignment-improving step **130** can include extracting position information regarding the lens **5** from the generated image **122**, and adjusting a position of at least one of the eye **1** or the docking unit **200** in relation to the extracted position information. In some implementations, other internal eye-structures can be targeted, such as the nucleus of the lens, or a retinal structure.

In an implementation, the surgeon can analyze the y-z image **122**, generated by the imaging step **120**, and determine the offset Δ of the lens center **14** from the optical axis **202** of the docking unit **200**. Based on this determination, the surgeon can shift either the eye, or the docking unit, or both, to overcome this Δ offset, as indicated by arrow **130a**. This adjustment-improving step **130** can reduce or even eliminate the offset Δ between the lens center **14** and the optical axis **202**. Typically, this shift **130a** can offset the optical axis **202** of the docking unit **200** from the optical axis **12** of the lens **5**.

The shift **130a** may be performed iteratively because in the first try the surgeon may not have determined the offset Δ precisely. To remedy this, in some implementations the alignment-improving step **130** may be followed by a repeated imaging step **120'** to determine how the offset Δ was changed by the shift **130a**. This repeated imaging step **120'** can be followed by a repeated alignment-improving step **130'** based on the updated image **122'** generated by the repeated imaging step **120'**, and so on. In efficient implementations, the offset Δ is reduced step-by-step. In other implementations, even if Δ increases during a step, subsequent steps reduce it eventually.

The shift **130a** can be performed by giving a verbal command to the patient to move his/her eye, or by physically moving the patient's head, or the surgical bed the patient is resting on, or by manually moving the patient's eye, or by moving a fixation light of a fixation light source, or by moving a directing light on a directing light display, in either case directing the patient to follow the light with his eye, or by moving the docking unit **200** in an x-y plane via moving a gantry or an articulated arm. In implementations using two piece docking units, the piece which was attached to the eye, such as a gripper, can be used to move or rotate the eye. The fixation or directing light can be directed either into the surgical eye or into the non-surgical eye. These adjustments can be performed manually by the surgeon, or by operating one or more electric actuators, or by a computer. In some cases, more than one of the above types of shifts can be performed jointly.

FIG. 7 also illustrates that in other implementations the alignment-improving step **130** may include extracting orientation information regarding the lens **5** or another targeted

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internal structure of the eye from the generated image **122**, and adjusting an orientation of at least one of the eye **1** or the docking unit **200** in relation to the extracted orientation information.

In an implementation, the surgeon can analyze the y-z image **122**, generated by the imaging step **120**, and determine the angle α between the optical axis **16** of the lens **5** and the optical axis **202** of the docking unit **200**. Based on this determination, the surgeon can rotate either the eye, or the docking unit, or shift the docking unit, or adjust an optical path of the laser beam in the laser surgical system **50** to overcome this a misalignment. The option of rotating the eye is indicated by arrow **130b**. This alignment-improving step **130** can reduce or even eliminate the angle α between the optical axis **16** of the lens **5** and the optical axis **202** of the docking unit **200**. This alignment-improvement is typically achieved by introducing an angle between the optical axis **12** of the eye and the optical axis **202** of the docking unit **200**, as indicated by the dotted line.

The rotation **130b** may be performed iteratively because in the first try the surgeon may not have determined the angle α precisely. To remedy this, in some implementations the alignment-improving step **130** may be followed by a repeated imaging step **120'** to determine the angle α' after the rotation **130b** from a repeated image **122'**, followed by a repeated alignment-improving step **130'** based on the image **122'** generated by the repeated imaging step **120'** and so on. In efficient implementations, the angle α is reduced step-by-step. In other implementations, even if α increases during a step, subsequent steps eventually reduce it.

The rotating step **130b** can be performed by giving a verbal command to the patient to rotate his/her eye, or by manually rotating the patient's head, or by physically rotating the patient's eye, or by moving a fixation light of a fixation light source, or a directing light displayed on a display, in either case directing the patient to follow the light with his eye, or by moving or rotating the docking unit **200** in the x-y plane via moving a gantry or an articulated arm. The fixation or directing light can be directed either into the surgical eye or into the non-surgical eye. In implementations using two piece docking units, the piece which was attached to the eye, such as a gripper, can be used to move or rotate the eye. These adjustments can be performed manually by the surgeon, or by operating one or more electric actuators, or by a computer. In some case, more than one of the above types of shifts can be performed jointly.

FIGS. 8A-B illustrate an outcome of the imaging step **120** and alignment-improving step **130**.

FIG. 8A illustrates that after a successful alignment-improving step **130**, a shifted target pattern circle **111'** may have become concentric with the lens **5** instead of the pupil **4**. Correspondingly, the shifted linear scanning line **121'**, across the shifted center **118'** of the target pattern circle **111'**, can now go through the center **14** of the lens **5** instead of the center of the pupil **4**.

Some implementations may display both the first target pattern circle **111** concentric with the pupil **4**, as well as a second target pattern **111'** which is shifted by the alignment-improving step **130** to be concentric with the lens **5**.

FIG. 8B illustrates that after an efficient alignment-improving step **130**, a repeated imaging step **120'** may record a cross-sectional y-z image **122'** showing that the center **14** of the lens now lies on the optical axis **202** of the docking unit **200**. Further, the images of the anterior and posterior capsule segments **5a'** and **5p'** after the relative rotation and shift of the eye and the docking unit **200**, are close to symmetric, indi-

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cating that the optical axis **16** of the lens is approximately aligned with the optical axis **202** of the docking unit **200**.

Achieving alignment of the docking unit **55/200** with the hard-to-see, displaced and tilted lens **5** instead of the visible pupil **4** with such an improved precision is one of the benefits of the image-guided docking method **100**.

FIG. **9** illustrates that an implementation of a related image-guided docking method **300** may include the steps of:

A video imaging step **310**, for generating a video microscope image of a portion of the eye;

A centering step **320**, for centering a docking tip based on the video microscope image;

An OCT imaging step **330** for generating an OCT image of a portion of the eye;

A distancing step **340** for determining a distance of the docking tip from the cornea based on the OCT image;

A moving step **350** for using the determined distance to move the docking tip towards the cornea of the eye;

A determining step **360** for determining a position or an orientation of a lens of the eye based on the OCT image;

An aligning step **370** for aligning the docking tip with a lens of the eye by instructing the patient with verbal commands, or adjusting a directing light or moving a gantry; and

A docking step **380** for applying suction to dock the docking tip.

Several of the steps **310-380** of the method **300** can proceed analogously with the corresponding steps **110-140** of the method **100**. In addition, the distance-determining step **340** can include determining the distance between the cornea **2** of the eye and the docking tip, which can be the docking unit **55** or **200**, or any other patient interface. In this step **340**, the distance from the docking tip can be based on a reference point. This reference point can be located in the optical system of the surgical laser system **50**, for example in the objective **54**. This reference point can be movable, and may be adjusted or offset based on various considerations.

FIG. **10** illustrates an OCT imaging system **457** to illustrate the details of the imaging step in greater detail. The OCT imaging system **457** can include an OCT imaging unit **458** and an OCT x-y scanner **459**.

The principles of the operation of OCT imaging systems are well known and documented. The OCT system **457** can be a (a) time domain, a (b) swept source or a (c) spectrometer based OCT. The (a) and (b) types of OCT imaging systems use a narrow band OCT light source **410** and scan the beam's focal point in the z-direction, thus they provide imaging information corresponding to different z-depths sequentially in time. The (a) type time domain OCT systems move a reference mirror, whereas the (b) type swept source OCT systems sweep the wavelength of the laser beam.

The (c) type spectrometer based OCT systems utilize a broad band OCT imaging light source **410** and capture images from a range of z-depths essentially simultaneously, or in parallel, corresponding to the different wavelengths within the broad band of an OCT imaging light source. Because of this parallel imaging aspect, spectrometer-based OCT systems can be substantially faster than sequential OCT systems. The (b) and (c) type OCT systems are sometimes referred to as frequency domain OCT systems.

All types of OCT imaging units **458** can include an OCT light source **410**, an OCT reference mirror **413** and a beam splitter **417**. Among the sequential OCT systems, for the (a) type time domain OCT, the OCT light source **410** can be a narrow band laser and the reference mirror **413** movable for z-scanning. For the (b) type swept source OCT, the reference mirror need not be movable as the wavelength of the light

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source **410** is varied. For (c) parallel OCT systems, the OCT light source **410** can emit a broadband imaging light.

The OCT imaging beam can be guided by the OCT beam x-y scanner **459**, directed to the eye via an objective **454** and a docking unit **455**. The OCT x-y scanner **459** can scan the OCT imaging beam in the eye in the x and y directions. In sequential OCT systems the beam is z scanned by moving either the reference mirror **413** or by sweeping the wavelength of the OCT light source **410**. In parallel OCT systems, no z-scanning is performed, as the different wavelengths carry the imaging information corresponding to different z depths essentially simultaneously.

In all these system, the OCT imaging beam returned from the eye can be unified with the reference beam returning from the OCT reference mirror **413** at the beam splitter **417**. This unified beam carries the imaging information in a complex interference pattern that is recorded by an OCT camera **420**.

For sequential OCT systems this OCT camera **420** can be simple, e.g. including a photodetector. For parallel OCT systems the OCT imaging unit **458** may include a spectrometer, such as a prism or a grating (not shown explicitly) that resolves the broad band imaging light into its different wavelength components, and deflects the different wavelength components to different spatial angles. In some parallel OCT systems the OCT camera **420** may include a linear array of CCD detectors to capture these diverging rays with different wavelength, each carrying interference information, specific for its own wavelength. In others, a two dimensional CCD array can be used. The amplitude of the resolved diverging rays can be recorded in the individual pixels of the CCD array of the OCT camera **420**. Some high resolution OCT cameras **420** can involve hundreds or even thousands of pixels.

The imaging process can be controlled by an imaging sync block **470**, which may get its sync signal from a later-specified output unit. The image data from the OCT camera **420** can be forwarded to an OCT analyzer **480**, synchronized by the imaging sync block **470**. In parallel OCT systems the OCT analyzer **480** may include a processor to perform a Fast Fourier Transform (FFT). The FFT converts the interference information of different wavelength components into image information corresponding to different z-depths. After the FFT, the transformed OCT image data represent image information corresponding to a range of z-depths. This transformed OCT image data may be forwarded to a processor **430**, which can generate an OCT image and output the generated OCT image towards a display **490**.

Next, an OCT scanning-beam-controller system will be described that solves the difficulties of the operation of some existing OCT scanning-beam-controllers which are described next.

In some OCT imaging systems the processor **430** can multitask and perform more than one function in an interleaved, parallel or overlapping manner. To carry out these functions, the processor may perform an "interrupt" by switching from e.g. the task of scanning the beam to another task and back. Such interrupts, however short, can cause problems, since during the time when the scanning is stopped or frozen by the interrupt, the laser beam may remain pointed to the same position. This scanning-freeze can disrupt the timing of the x-y scan, introducing an error and noise into the coordinates of the imaged location. This timing error in the outputted scanning data can lead to delays that may reach 50, 100 or more microseconds: a phenomenon sometimes called jitter. Further, the extended exposure to the laser beam can cause damage to the sensitive eye tissue.

In addition, since the processor typically communicates with input/output agents through a system bus, this output

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mode only provides slow data transfer rates, since several agents may access the bus simultaneously, all demanding a fraction of its cycle time. Further, to manage these competing demands, a portion of the cycle of the system bus is typically taken up by control signals. And if an OCT imaging system is designed to avoid this scanning-freeze by the processor outputting the scanning data to an output unit in a single-task mode, e.g. through a dedicated link, then the processor cannot perform other functions during this outputting step, such as computing the next scanning pattern. All these designs and constraints slow down the performance of such systems considerably.

Implementations of the presently described OCT scanning-beam-controller can overcome these difficulties by employing an efficient design. The OCT scanning-beam-controller can include the processor 430 and an analog input-output board 435. The processor 430 can compute scanning data for a scanning pattern. This scanning data can include e.g. a sequence of x-y coordinates where the OCT imaging beam will be directed in the target region in the course of scanning. For sequential, z-scanning OCT systems, the scanning data can include x-y-z coordinates. As described above, the OCT scanning pattern can be a wide variety of patterns, including lines, arcs, loops, circles, spirals, raster and grid patterns.

The processor 430 can compute the scanning data, as well as perform its other described functions in connection to a storage medium that stores a computer code or instruction set to facilitate these functions of the processor.

The analog input-output board 435 can include a local or dedicated memory controller 440, also referred to as a direct memory access engine 440, or DMA engine 440. The DMA engine/memory controller 440 can manage a transfer of the computed scanning data, indirectly or directly, from the processor 430 toward a data buffer 450. The data buffer 450, coupled to the local memory controller 440 can store the scanning data and output the scanning data towards an output digital-analog converter 460, or output DAC 460. The output DAC 460 can be coupled to the data buffer 450 and can (i) convert selected outputted scanning data to analog scanning signals, and (ii) output the scanning signals towards the OCT beam x-y (or x-y-z) scanner 459.

FIG. 11 illustrates an implementation of the OCT scanning beam-controller. The processor 430' can be coupled to a bus 432, such as a PCI bus 432. The OCT scanning-beam-controller can also include a processor memory 433. The processor 430' can output the computed scanning data to the processor memory 433. The dedicated DMA engine 440' can transfer the scanning data from the processor memory 433 to the data buffer 450' which can be e.g. a first-in-first-out (FIFO) memory. The FIFO buffer memory 450' can store the scanning data and output the stored scanning data to the output DAC 460' when prompted. In some implementations, the processor can output the scanning data to the analog input-output board 435 through a dedicated memory bus or local bus instead of a PCI bus 432. In other implementations, there can be even a direct connection between the processor and the DMA engine 440'.

In relation to the above described problems with other systems, embodiments of the present OCT scanning-beam-controller offer a fast scanning operation as (i) the FIFO memory 450' can output the stored scanning data in an uninterrupted manner; (ii) the output mode can be a fast data transfer mode, such as a burst mode; and (iii) the output can be performed without sending the scanning data through the shared bus 432, the processor memory 433, or the processor 430'.

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For all these reasons, the outputting of the scanning data will not be interrupted by competing tasks, or slowed down by the slow data transfer characterizing the shared bus 432.

Further, since the FIFO memory 450' drives the outputting of the scanning data, the processor 430' is free to perform other functions in parallel with the data output, such as processing an image, or computing new scanning data corresponding to a scanning pattern, or performing a control function.

In addition, the output of the scanning data by the data buffer 450' to the output DAC 460' is not slowed down by an interrupt by the processor 430 or another system agent either since the output proceeds from the data buffer 450' through a dedicated channel on the analog input-output board 435 instead of the shared bus 432. Such implementations can reduce the jitter considerably, such as keeping it below 50, 40, or even 20 microseconds.

In some implementations, the output DAC 460' can convert the received digital scanning data into analog scanning signals and output the scanning signals to x and y galvo-controllers 56a and 56b, or some other types of scanning-controllers that control x and y galvo mirrors, or redirector elements, to scan the OCT imaging beam according to the scanning pattern, coded in the scanning data. Some implementations may have an integrated x-y galvo-controller that controls a minor capable of rotating around two axes.

The output DAC 460' can also output synchronizing signals to the imaging sync block 470' coupled to the OCT imaging camera 420 to record the returned OCT imaging beam synchronously with the scanning of the OCT imaging beam. The synchronizing signals can be based on synchronizing data, inserted by the processor 430' into the scanning data.

In addition, the imaging step 120 can include computing homing data corresponding to a homing pattern connecting an ending point of a first imaging step to a starting point of a subsequent second imaging step. This step can be useful in implementations where the first imaging step ends by simply stopping the output of the scanning data, thus leaving the scanning x and y galvos 56a-b in a non-standard position and the imaging beam pointed to a non-standard target point. This non-standard point is typically different from the starting point of the subsequent second imaging step, thus necessitating the "homing" of the x and y galvos 56a-b by computing and outputting homing data, so that the imaging beam can start the subsequent second imaging step from a well-defined starting point.

As an example, the first imaging step may include scanning the x and y coordinates of the imaging beam along a first circle of a first radius. If the second imaging step includes scanning along a second circle of a second radius, then the first imaging step can be followed by computing homing data that define a path from the endpoint of the first circular scan with the first radius to the starting point of the second circular scan with the second radius.

Such implementations can avoid moving the imaging beam back to a standard point, e.g. to a center, origin, or otherwise unbiased point, thus saving additional time and further accelerating the scanning operation.

The computing of the homing data can be also useful in implementations where at the end of the first imaging step the x and y galvos 56a and 56b are returned to a neutral position, as it facilitates the computing of the starting position of a second imaging step in relation to the neutral position.

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In some implementations, the speed of the output of the output DAC 460/460' can be so fast that an operating speed of the imaging system 457 can be limited by an integration time of the OCT camera 420.

In some implementations, the output DAC 460/460' can output the scanning signals at a rate within one of the following ranges: 1 Hz-1 MHz, 100 Hz-1 MHz, or 1 kHz-100 kHz.

In some implementations, the rate of output for the scanning signals can be adjustable according to the requirements of the imaging task and pattern.

Once the imaging step 120 is completed, the alignment-improving step 130 can include providing a verbal command to a patient based on the image of the internal structure of the eye, such as the lens 5.

The alignment-improving step 130 can also include providing a fixation light beam, asking the patient to look at the fixation light, and adjusting the fixation light based on the image provided by the imaging step 120. The fixation light can be provided into the surgical eye, through the main optical pathway of the laser surgical system 50, or through a separate fixation light system. In some cases the fixation light can be provided to the non-surgical eye.

The alignment-improving step 130 can be started (i) before the docking unit 55/200 makes contact with the eye; (ii) after the docking unit 55/200 makes contact with the eye but before an application of a vacuum; or (iii) after an application of a partial vacuum in relation to the docking unit 55/200 that still allows some degree of alignment modification.

The partial vacuum, or suction, can be applied, for example, through a suction ring or suction skirt, which can be part of the docking unit 55/200. The suction can be applied after the eye was brought into physical contact with the eye.

The docking method 100 can be performed as part of a surgical process or a diagnostic process. In other implementations, the docking method 100 can be part of an imaging procedure, which is not part of a surgical or a diagnostic procedure, such as an identification process.

The steps 110-140 can involve program codes or instruction sets that are stored in the imaging system 57. The code can be stored e.g. in a dedicated memory or in a memory that is part of another functional block. The aligning step 110 can involve a code stored in a memory related to the video microscope 56. The imaging step 120 can involve storing the scanning patterns or scanning data generated by the processor 430 in a dedicated or integrated memory, or storing scanning data in the data buffer 450. The alignment-improving step 130 can include using a memory unit for storing the generated image to help improving the alignment of the docking unit 55 with the lens of the eye 1 in relation to the generated image. The docking step 140 can also use a stored program to guide and control the docking unit 200 docking with the eye.

FIG. 12 illustrates that an implementation of a fast imaging method 500 can include:

A step 510 of computing scanning control data by the processor 430/430';

A step 520 of storing the scanning control data into the processor memory 433 by the processor 430;

A step 530 of setting up the dedicated memory controller 440/440' for a scanning operation by defining operation parameters, such as a scanning output rate;

A step 540 of transferring scanning control data from the processor memory 433 to the data buffer 450/450' at least partially under the control of the dedicated memory controller 440/440';

A step 550 of notifying the processor 430/430' by the dedicated memory controller/DMA engine 440/440' that the transfer of the scanning control data has been completed;

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A step 560 of instructing the dedicated memory controller 440/440' by the processor 430/430' to start fast output of the scanning control data;

A step 570 of transferring the scanning control data from the data buffer 450/450' to the output DAC 460/460' at least partially under the control of the dedicated memory controller 440/440', the output DAC 460/460' converting the digital scanning control data to analog scanning control signals, and the output DAC 460/460' outputting the analog scanning control signals to the x and y scanners 56a and 56b, and to the sync block 470;

A step 580 of notifying the processor 430/430' by the dedicated memory controller 440/440' that the output process is complete.

In the step 570, the transferring the scanning control data from the data buffer 450/450' can be performed in a fast transfer mode, such as a burst mode, or a page mode, or any similarly fast transfer modes.

In the step 570, the transferring of the scanning control data from the data buffer 450/450' can be performed without sending the scanning control data through the bus 432 that connects the local memory controller 440, the processor 430, and the processor memory 433.

In the step 570, the transferring step can also include transferring the scanning control data in parallel with the processor 430 processing an image or computing scanning data corresponding to a scanning pattern.

In the step 570, the transferring step can also include transferring the scanning data without an interrupt by another system agent, thereby keeping a jitter of the scanning data below 50, 40, or 20 microseconds.

In an implementation 600 of the above method 500, the above steps can be organized into the following steps:

A step 610 of computing scanning control data by a processor can include the step 510;

A step 620 of storing the scanning control data into a data buffer partially by a local memory controller can include the steps 520, 530, 540, and 550;

A step 630 of transferring the scanning control data from the data buffer in a fast transfer mode to a converter-output module can include the steps 560 and elements of the step 570; and

A step 640 of outputting scanning signals to scanning controllers, the scanning signals converted from the scanning control data by the converter-output module can include elements of the step 570.

While this specification contains many specifics, these should not be construed as limitations on the scope of any invention or of what may be claimed, but rather as descriptions of features specific to particular embodiments. Certain features that are described in this specification in the context of separate embodiments can also be implemented in combination in a single embodiment. Conversely, various features that are described in the context of a single embodiment can also be implemented in multiple embodiments separately or in any suitable subcombination. Moreover, although features may be described above as acting in certain combinations and even initially claimed as such, one or more features from a claimed combination can in some cases be excised from the combination, and the claimed combination may be directed to a subcombination or variation of a subcombination.

The invention claimed is:

1. A docking method for an ophthalmic system, the method comprising:
aligning a docking unit of the ophthalmic system and an eye;

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generating an image of an internal structure of the eye by an optical coherence tomographic imaging system after aligning the docking unit and the eye;
 improving an alignment of the docking unit with the internal structure of the eye in relation to the generated image; and
 docking the docking unit to the eye with the improved alignment the generating the image step comprising:
 computing scanning data by a processor corresponding to a scanning pattern;
 storing the scanning data in a dedicated data buffer;
 transferring the scanning data by the dedicated data buffer to an output module partially under the control of a dedicated memory controller;
 outputting scanning signals by the output module to one or more scanners based on the scanning data; and
 scanning an imaging beam with the one or more scanners according to the scanning signals.

2. The method of claim 1, the aligning the docking unit step comprising:
 using a first imaging system to align a target pattern of the ophthalmic system in relation to a feature of the eye.

3. The method of claim 2, wherein:
 the first imaging system is one of a microscope or a video microscope;
 the target pattern of the ophthalmic system includes at least one of a center of a contact lens, a center of the docking unit, a docking circle, or a docking cross-hair; and
 the feature of the eye is at least one of
 a center of a region of an iris, a pupil, a cornea, a limbus, or a lens; or
 a circular formation related to a region of the iris, the pupil, the cornea, the limbus or the lens.

4. The method of claim 1, the improving an alignment step comprising:
 extracting position information regarding the internal structure of the eye from the generated image; and
 adjusting a position of at least one of the eye or the docking unit in relation to the extracted position information.

5. The method of claim 1, the improving an alignment step comprising:
 extracting orientation information regarding the internal structure of the eye from the generated image; and
 adjusting an orientation of at least one of the eye or the docking unit in relation to the extracted orientation information.

6. The method of claim 1, the computing the scanning data step comprising:
 implementing a scanning pattern that includes at least one of a linear pattern, a circular pattern, an oval pattern, a loop pattern, an arc pattern, a raster pattern, an x-y pattern, a crosshair pattern, a star pattern, a spiral pattern, and a pattern with outlying points.

7. The method of claim 1, the computing the scanning data step comprising:
 including synchronizing signals into the scanning data by the processor.

8. The method of claim 1, the computing the scanning data step comprising:
 computing homing data corresponding to a homing pattern connecting a starting point of the scanning pattern to a previously set point.

9. The method of claim 1, the storing the scanning data step comprising:
 storing the scanning data in a processor memory; and

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transferring the stored scanning data from the processor memory to the dedicated data buffer partially under the control of the dedicated memory controller.

10. The method of claim 9, wherein:
 the dedicated memory controller comprises a direct memory access engine; and
 the dedicated data buffer comprises a first-in-first-out memory.

11. The method of claim 1, the transferring the scanning data step comprising:
 outputting the scanning data by the dedicated data buffer to the output module in a fast data transfer mode.

12. The method of claim 1, the transferring the scanning data step comprising:
 outputting the scanning data from the dedicated data buffer without sending the scanning data through at least one of a bus connecting the dedicated memory controller and the processor,
 the processor memory, or
 the processor.

13. The method of claim 1, the transferring the scanning data step comprising:
 outputting the scanning data in parallel with the processor performing at least one of
 processing an image,
 computing scanning data corresponding to a scanning pattern, or
 performing a control function.

14. The method of claim 1, the transferring the scanning data step comprising:
 receiving the scanning data by the output module without an interrupt by another system agent,
 thereby keeping a jitter of the scanning data below 40 microseconds.

15. The method of claim 1, the outputting the scanning signals step comprising:
 converting the scanning data into analog scanning signals by the output module, wherein the output module includes a digital-analog converter.

16. The method of claim 1, the scanning an imaging beam step comprising:
 receiving the outputted scanning signals by a scanning controller and an imaging synchronizer, wherein
 the scanning signals comprise synchronizing signals;
 repeatedly adjusting the one or more scanners by the scanning controller according to the scanning signals to scan the imaging beam; and
 repeatedly synchronizing an imaging camera by the imaging synchronizer according to the synchronizing signals.

17. The method of claim 16, wherein:
 the scanning controller comprises at least one galvo-controller; and
 the imaging synchronizer comprises at least one ophthalmic coherence imaging camera controller.

18. The method of claim 1, wherein:
 an integration time of an image recording device is a limiting factor of an operating speed of an imaging system.

19. The method of claim 1, the outputting the scanning signals step comprising:
 outputting the scanning signals at a rate within one of the following ranges:
 1 Hz-1 MHz, 100 Hz-1 MHz, or 1 kHz-100 kHz.

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20. The method of claim 1, the outputting the scanning signals step comprising:

adjusting an output rate of the output of the scanning signals.

21. The method of claim 1, the improving the alignment step comprising at least one of:

providing a verbal command to a patient to move his eye, moving the patient's head,

moving a surgical bed the patient is resting on,

moving the patient's eye,

moving the docking unit via moving a gantry or an articulated arm, and

using a gripper to move the eye,

based on the image of the internal structure of the eye.

22. The method of claim 1, the improving the alignment step comprising:

adjusting at least one of a fixation beam or a directing light to improve the alignment of the eye and the docking unit; and

directing the patient to follow the fixation beam or the directing light with his eye.

23. The method of claim 1, the improving the alignment step comprising:

starting the improving the alignment step

before the docking unit makes contact with the eye,

after the docking unit makes contact with the eye but

before an application of a partial vacuum to the docking unit, or

after an application of a partial vacuum.

24. The method of claim 1, the docking step comprising:

sensing a distance between a reference point of the docking unit and an outer layer of the eye; and

lowering the docking unit according to the sensed distance.

25. The method of claim 24, wherein:

the reference point is adjustable.

26. The method of claim 1, the docking step comprising:

bringing the docking unit into physical contact with the eye; and

applying suction through a portion of the docking unit after the docking unit makes physical contact with the eye.

27. An imaging controller for an ophthalmic system, comprising:

a processor that computes scanning data for a scanning pattern of an optical coherence tomographic imaging system;

a local memory controller that partially manages a transfer of the computed scanning data from the processor to a dedicated data buffer, wherein

the dedicated data buffer is configured to store the scanning data and to output the scanning data; and

an output digital-analog converter, coupled to the dedicated data buffer that converts selected scanning data to analog scanning signals and outputs the scanning signals to the optical coherence tomographic imaging system.

28. The imaging controller of claim 27, the local memory controller comprising:

a direct memory access engine.

29. The imaging controller of claim 27, the dedicated data buffer comprising:

a first-in-first-out memory that outputs the stored scanning data in a fast data transfer mode.

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30. The imaging controller of claim 27, further comprising: a processor memory; and

a bus, coupled to the processor, the local memory controller and the processor memory, Wherein

the processor is configured to output the computed scanning data to the processor memory through the bus; and

the local memory controller is configured to transfer the scanning data from the processor memory to the dedicated data buffer through the bus.

31. The imaging controller of claim 30, wherein:

the dedicated data buffer is configured to output the scanning data without sending the scanning data through at least one of

the bus, the processor memory, or the processor.

32. The imaging controller of claim 27, wherein:

the processor is configured to perform at least one of

processing an image and computing scanning data,

while the dedicated data buffer outputs the scanning data.

33. The imaging controller of claim 27, wherein:

the output digital-analog converter is coupled to the dedicated data buffer so that the scanning data, outputted by the dedicated data buffer is received without an interrupt by another system agent,

thereby keeping a jitter of the scanning data below 40 microseconds.

34. The imaging controller of claim 27, wherein:

the output digital-analog converter is configured to output the scanning signals to x and y scanning controllers to scan an imaging beam; and

synchronizing signals to an imaging camera to record a returned imaging beam synchronously with the scanning.

35. A method of controlling an ophthalmic imaging, the method comprising the steps of:

computing scanning control data by a processor for an optical coherence tomographic imaging system;

storing the scanning control data into a dedicated data buffer partially under the control of a memory controller;

transferring the scanning control data from the dedicated data buffer to a signal converter through a dedicated channel; and

sending scanning signals to a scanning controller by an output module, wherein

the scanning signals are converted from the scanning control data by the signal converter.

36. The method of claim 35, the storing the scanning control data step comprising:

storing the computed scanning control data in a processor memory; and

moving the scanning control data from the processor memory to the dedicated data buffer.

37. The method of claim 36, the transferring the scanning control data step comprising:

transferring the scanning data from the dedicated data buffer without sending the scanning data through at least one of

a bus connecting the local memory controller and the processor,

the processor memory, or

the processor.

38. The method of claim 35, the transferring the scanning control data step comprising:

transferring the scanning data in parallel with the processor performing at least one of:

processing an image; and

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computing scanning data corresponding to a scanning pattern.

39. The method of claim **35**, the transferring the scanning control data step comprising:

transferring the scanning data without an interrupt by 5
another system agent,
thereby keeping a jitter of the scanning data below 40
microseconds.

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40. The method of claim **35**, wherein:

the local memory controller includes a direct memory access engine; and

the dedicated data buffer is a first-in-first-out memory.

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