(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
4 August 2016 (04.08.2016)

WIPO | PCT

(10) International Publication Number
WO 2016/120767 A1

(51) International Patent Classification:
G09B 23/28 (2006.01) *A61C 9/00* (2006.01)

(21) International Application Number:
PCT/IB2016/050333

(22) International Filing Date:
22 January 2016 (22.01.2016)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
62/108,263 27 January 2015 (27.01.2015) US
14/993,798 12 January 2016 (12.01.2016) US

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(81) Designated States *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, JP, KE, KG, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

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WO 2016/120767 A1

(54) Title: METHOD AND SYSTEM FOR ORAL-CAVITY-IMAGING-AND-MODELING EQUIPMENT

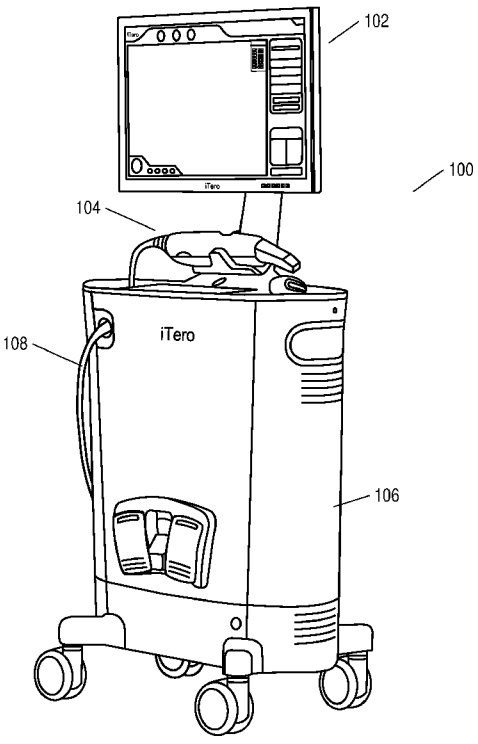

FIG. 1

(57) Abstract: The current document is directed to methods and systems for guiding a wand for scanning one or more surfaces of a three-dimensional, solid object, in particular, within the oral cavity of a patient, as well as for providing semi-automated and automated training to technicians who use oral-cavity-imaging-and-modeling systems to accurately and efficiently generate three-dimensional models of patients' teeth and underlying tissues. The methods and systems are implemented either as subsystems within oral-cavity-imaging-and-modeling systems or as separate system in electronic communication oral-cavity-imaging-and- modeling systems. The methods and systems use an already generated, digital, three- dimensional model of a portion of the oral cavity of a particular patient or of a physical model of a portion of an oral cavity to compute a temporal, translational, and rotational trajectory of an oral-cavity-imaging-and-modeling endoscope, or wand, during a training scan.

Published:

— *with international search report (Art. 21(3))*

METHOD AND SYSTEM FOR ORAL-CAVITY-IMAGING-AND-MODELING EQUIPMENT

TECHNICAL FIELD

The current document is directed to automated and semi-automated training methods and systems and, in particular, to methods and systems that train technicians to effectively employ oral-cavity-imaging-and-modeling systems.

BACKGROUND

Prior to the development of oral-cavity-imaging-and-modeling systems, dental practitioners employed mechanical-impression methods to create three-dimensional models of teeth and underlying tissue in order to facilitate fabrication of various types of prostheses, including crowns and bridges. The mechanical-impression technologies generally involved biting, by a patient, into a viscous, thixotropic material that retains an accurate impression of the patient's teeth and underlying tissue when the material is lifted off from the patient's teeth. The material may serve as a mold for casting a positive three-dimensional model of the patient's teeth and underlying gum tissue or as a mold for casting a prosthetic device. While mechanical-impression technologies have been used by dental practitioners for many decades, mechanical-impression technologies are associated with a variety of deficiencies, including a relatively large probability that the impression may be inadvertently altered or damaged during removal of the hardened, viscous, thixotropic material from the patient's teeth as well as during transportation of the impression to laboratories where positive three-dimensional models are cast and prostheses are fabricated. In addition, the procedure is time-consuming and unpleasant to many patients.

More recently, semi-automated oral-cavity-imaging-and-modeling systems have been developed to electronically create digital, three-dimensional models of teeth and underlying tissues from images of a patient's oral cavity captured by an electro-optical-mechanical endoscope, or wand, that is guided by a technician within a patient's oral cavity in order to collect a sufficient number of two-dimensional images from which a three-dimensional digital model of the patient's

teeth and underlying tissues is computationally generated. The oral-cavity-imaging-and-modeling systems have proven to be faster, more accurate and robust, and more cost effective than mechanical-impression technologies. However, the efficiency and cost effectiveness of oral-cavity-imaging-and-modeling systems may significantly vary with respect to the experience and skill of the technicians who use the oral-cavity-imaging-and-modeling systems to generate three-dimensional models of patients' teeth and underlying tissues.

SUMMARY

The current document is directed to methods and systems that provide semi-automated and automated training to technicians who use oral-cavity-imaging-and-modeling systems to efficiently and accurately generate three-dimensional models of patients' teeth and underlying tissues. The three-dimensional models may be subsequently used for fabricating dental prostheses, treatment planning, monitoring the dental health of patients, providing simulations of proposed restorations, and for other dental-care-related uses. The training methods and systems are implemented either as subsystems within oral-cavity-imaging-and-modeling systems or as separate system in electronic communication oral-cavity-imaging-and-modeling systems. These training methods and systems use an already generated, digital, three-dimensional model of a portion of the oral cavity of a particular patient or of a physical model of a portion of an oral cavity to compute a temporal, translational, and rotational trajectory of an oral-cavity-imaging-and-modeling endoscope, or wand, during a training scan. The temporal, translational, and rotational trajectory is used for a variety of different types of instruction and instructional feedback to facilitate training of technicians.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 shows one type of oral-cavity-imaging-and-modeling system.

Figure 2 shows an oral-cavity-imaging-and-modeling system being used by a technician to image the oral cavity of a patient.

Figure 3 illustrates lower and upper rows of teeth and underlying tissue.

Figure 4 illustrates one possible trajectory of a point on an image-collecting surface of an endoscope within the oral cavity of a patient during a scan of the lower and upper rows of teeth.

Figures 5A-K illustrate characteristics of a wand trajectory during an imaging scan.

Figure 6 provides a general architectural diagram for various types of computers.

Figure 7A illustrates generalized hardware and software components of a general-purpose computer system, such as a general-purpose computer system having an architecture similar to that shown in Figure 6.

Figure 7B illustrates generalized hardware and software components of a general-purpose computer system, such as a general-purpose computer system having an architecture similar to that shown in Figure 6, which includes a virtualization layer.

Figure 8 illustrates the image-capture subsystem of one implementation of an oral-cavity-imaging-and-modeling system.

Figure 9 illustrates image capture by the oral-cavity-imaging-and-modeling system over a small portion of a scan trajectory.

Figure 10 illustrates generation of an accurate three-dimensional digital model from two-dimensional images.

Figures 11A-B illustrate use of two-dimensional images to generate a three-dimensional model of an imaged object.

Figures 12A-B illustrate the need for adequate sampling frequency over spatial dimensions.

Figure 13 shows a particular image-capture event with respect to a row of teeth and underlying tissue.

Figures 14A-B illustrate determination of a trajectory point corresponding to a two-dimensional photographic or three-dimensional surface image captured during a training session.

Figures 15A-G illustrate one example user interface for an automated or semi-automated training system that trains technicians to efficiently and accurately scan oral cavities using oral-cavity-imaging-and-modeling systems.

Figure 16 illustrates use of one implementation of the automated or semi-automated training system that trains technicians to efficiently and accurately scan oral cavities using oral-cavity-imaging-and-modeling systems.

Figure 17 illustrates two different data structures that are maintained by the training subsystem of an oral-cavity-imaging-and-modeling system during training sessions to facilitate the calculation and display of information by a training user interface and for other training purposes.

Figures 18A-H provide control-flow diagrams that illustrate implementation of one example automated training subsystem incorporated within an oral-cavity-imaging-and-modeling system for training oral-cavity-imaging-and-modeling-system technicians to efficiently and accurately scan patients.

DETAILED DESCRIPTION

The current document is directed to automated and semi-automated methods, and systems that incorporate the methods, for training oral-cavity-imaging-and-modeling-equipment technicians to efficiently and accurately scan the oral cavities of patients in order to acquire accurate, three-dimensional digital models of patients' teeth and gum tissue. These automated and semi-automated methods employ, as subjects for training, either particular individuals for whom three-dimensional oral-cavity models have already been generated or physical models of teeth and tissue associated with already generated three-dimensional digital models. Because, during training, a technician collects images from either a patient or physical model associated with an already generated three-dimensional digital model, images captured during training can be used, along with the already generated three-dimensional model, to accurately determine the position and orientation of the image-capturing endoscope, or wand, as the wand is guided by the technician during a training scan in certain implementations. In other implementations, at least the spatial position of the wand can be estimated to a useful degree of accuracy, and, in still other implementations, both the spatial position and orientation of the wand can be estimated to a useful degree of accuracy. This information, in turn, provides the basis for many different types of automated and semi-automated instructional feedback and guidance.

Figure 1 shows one type of oral-cavity-imaging-and-modeling system. The system 100 includes an electronic display screen 102, an endoscope 104, alternatively referred to as a "wand" or "optical wand," and a housing 106 that includes a processor-controlled computing system, a laser light source, imaging subsystems, and additional components. The wand 104 is connected to the components and subsystems within housing 106 by an electro-optical cable 108.

Figure 2 shows an oral-cavity-imaging-and-modeling system being used by a technician to image the oral cavity of a patient. As shown in Figure 2, the technician 202 holds and guides the wand 104 within a patient's mouth in order to acquire images of the patient's teeth and underlying tissue which are then used, by the processor-controlled computing system within the oral-cavity-imaging-and-modeling system 100, to generate a three-dimensional, digital model of the patient's teeth and underlying gum tissue. The model 204, or a partial model, may be rendered for display on the display screen 102 for viewing both by the technician 202 and patient 206. In addition, selected images acquired by the system 208 may be concurrently displayed. Once the technician has completed a sufficient number of scans, guiding the wand along different trajectories and in different orientations, a sufficient number of different two-dimensional photographic and three-dimensional surface images have been acquired by the system to generate a complete three-dimensional digital model of a portion of the patient's oral cavity. The digital model is saved in one or more files that can be downloaded to remote systems, including systems in laboratories where prostheses are fabricated, and can be stored as part of the patient history for a variety of subsequent uses, including developing treatment plans, monitoring dental health over long periods of time, generating simulations of proposed prostheses and treatments, facilitating explanation of conditions and pathologies to patients, and for many other uses.

Figure 3 illustrates lower and upper rows of teeth and underlying gum tissue. In Figure 3, the lower row of teeth 302 and upper row of teeth 304 are arranged in a planar fashion, as if the jaw were able to rotate nearly 180 degrees. Figure 4 illustrates one possible trajectory of a point on an image-collecting surface of an endoscope within the oral cavity of a patient during a scan of the lower and upper rows of teeth. A first scan of the lower row of teeth may follow the horseshoe-

shaped trajectory indicated by curve 402 and a second scan of the upper row of teeth may follow a horseshoe-like trajectory 404. Small arrows, such as arrow 406, indicate the path of light from the closest point on the patient's teeth to a reference point on the endoscope, or wand. During the scanning operation, as discussed further below, images are captured by the endoscope at various positions along the trajectory to produce a sequence of images from which a three-dimensional digital model is computationally constructed. As discussed further below, the wand has a position in three-dimensional space as well as a rotational orientation, and thus each point on the trajectory may be described in terms of three spatial coordinates, three rotational angles, and an absolute time or an elapsed time relative to the starting time of the scan. There are many different possible coordinate systems that can be used for both spatial position and rotational orientation. In general, multiple scans may be needed to generate an accurate three-dimensional model, each scan having a distinct trajectory. At any given point in the trajectory, the wand can capture a two-dimensional image and can additionally determine the distance between imaged features and surfaces and the wand.

Figures 5A-K illustrate characteristics of a wand trajectory during an imaging scan. Figure 5A shows a two-dimensional projection of the three-dimensional spatial component of two trajectories corresponding to two subscans of a row of teeth. The projection is carried out perpendicularly to the plane of the row of teeth discussed above with reference to Figures 3 and 4. A first subscan 502 starts at a point 504 at a first end 506 of the row of teeth and proceeds to the second, opposite end 508 of the row of teeth. The first subscan 502 is used to image the inner, or lingual, surfaces of the teeth in the row of teeth. A second subscan 510 begins at a point 512 at the second end of the row of teeth and proceeds back, in an opposite direction, to the first end 506 of the row of teeth. The second subscan 510 is used to image the exterior, or buccal, surfaces of the teeth.

The spatial trajectory of a reference point in the optical path of the wand, such as a point centered on a transparent window through which reflected light rays from the surfaces of teeth and tissue are received by the wand, is three-dimensional. Figure 5B shows the three-dimensional spatial trajectory corresponding to the two-dimensional projection of the spatial trajectory shown in Figure 5A. In

Figure 5B, the three-dimensional spatial subscan trajectories 514 and 516 are shown to have *z*-direction displacements, represented by dashed arrows, such as dashed arrow 518, from the two-dimensional projections of the subscan trajectories 502 and 510 shown as dashed curves in Figure 5B.

In Figures 5A-B, the subscan trajectories are relatively simple, planar curves. However, as shown in Figure 5C, the actual trajectories followed by the wand may be complex curves 520 and 522 with many points of inflection and many non-linear variations in the three spatial dimensions.

Figures 5D-G illustrate several of the possible types of images that may be acquired by an electro-optical-mechanical endoscope, or wand, during a scan of a patient's oral cavity. As shown in Figure 5D, one type of image is a digital photograph. The digital photograph 524 is a pixel-based encoding of a two-dimensional photographic image. In general, each pixel may be represented by 24 bits, including three eight-bit RGB color-intensity values, or pixels may be encoded by any of many other, alternative pixel-encoding schemes.

Figures 5E-G illustrate a depth-based encoding of a three-dimensional surface. For simplicity of illustration, the surface is shown as a portion of a cylinder, but complex surfaces, such as the surfaces of a number of adjacent teeth, can be imaged in the same fashion as the imaging of the cylindrical surface illustrated in Figures 5E-G. Figure 5E shows the cylindrical surface 526 overlying a two-dimensional coordinate grid 528. In the current example, the coordinate grid is planar, but non-planar coordinate surfaces may also be employed. As shown in Figure 5F, a distance between the coordinate-grid surface 528 and the cylindrical surface 526 in a particular direction, in this case a direction normal to the coordinate-grid plane, such as the distance 530 represented by a vertical arrow, can be computed from arbitrary points of the coordinate surface 528. Figure 5F shows numerous computed distances from the coordinate surface 528 to the cylindrical surface 526 illustrated as arrows, such as arrow 530. As shown in Figure 5G, a matrix of distances 532 can be stored to represented the shape of the surface, in the current example the cylindrical surface. Each value, such as the value 534, stored in the matrix represents the distance from the coordinate surface to the surface being imaged. In general, the distances are computed from the points of a grid or lattice so

that the row and column coordinates of a value correspond by a simple linear transformation to locations on the coordinate surface. This matrix 532 represents a second, different type of numerically encoded image. Thus, the wand can electronically and optically acquire both two-dimensional images, such as the photographic image shown in Figure 5D, as well as three-dimensional-surface images, such as the three-dimensional-surface image shown in Figure 5G. In the following discussion, the unqualified term "image" may refer either to a two-dimensional photographic image or a three-dimensional-surface image.

As shown in Figure 5H, the oral-cavity-imaging-and-modeling system captures two-dimensional photographic and three-dimensional surface images at various points along a trajectory. In Figure 5H, rectangles, such as rectangle 534, represent captured two-dimensional photographic and three-dimensional surface images when the wand has a spatial position indicated by the associated point, such as point 536 at a time indicated by a subscripted t, such as time t_0 538 at which image 534 is captured by the oral-cavity-imaging-and-modeling system. In Figure 5H, 13 images or sets images are illustrated to be captured at 13 different points on the spatial trajectory and at times t_0 through t_{12}. In an actual scan, hundreds to thousands of individual two-dimensional photographic and three-dimensional surface images may be captured. In certain systems, only two-dimensional photographic images are collected. In alternative systems, only three-dimensional surface images are collected. In the currently described system, both two-dimensional photographic and three-dimensional surface images are collected.

As shown in Figure 5I, the wand may have a variety of different rotational orientations at each point along a spatial trajectory. Representing the wand as a rectangular solid 540, Figure 5E illustrates that the rotational orientation of the wand can be expressed with three different rotational angles, or rotational coordinates, about three axes: a rotational angle θ about the x axis 542; a rotational angle φ about the y axis 544, and a rotational angle Ψ 546 about the z axis. The particular image captured at any point along the spatial trajectory, as illustrated in Figure 5H, depends not only on the spatial position of the wand when the image is captured, but also on the rotational orientation of the wand. Thus, specification of the

trajectory involves, at each point of the trajectory, three spatial coordinates as well as three rotational angles, or rotational coordinates.

Figure 5J illustrates the description of a wand trajectory. Each point on of the trajectory can be represented as a vector 550 in a seven-dimensional real space. The trajectory 552 is a time-ordered ordered set of trajectory points. Alternatively, a trajectory may be considered to be a sequence 554 of six-dimensional vectors 556 ordered in time along a time line 558. Depending on the ability for spatial position and orientation to be determined, lower-dimensional vectors may used those cases when less precise spatial-position and/or orientation information can be determined.

Figure 5K illustrates a trajectory envelope. In Figure 5K, a short, linear portion of a scan trajectory 560 is shown in a three-dimensional plot. A projection of this trajectory segment is shown as dashed line 562 in the *x*-*y* plane. Trajectory segment 560 may be a short, linear portion of an optimal trajectory that, when followed, leads to generation of an accurate three-dimensional digital model of the oral cavity under certain constraints. However, in many practical cases, there may be more than a single optimal trajectory and there may be many suboptimal but acceptable related trajectories, all of which lead to an accurate, three-dimensional digital model of the oral cavity. In general, a training system seeks to teach technicians to guide the wand within some extended envelope 564 that generally includes multiple optimal trajectories and multiple suboptimal, but acceptable trajectories 560. There may be multiple possible starting points for a scan, each starting point associated with its own trajectory envelope representing a set of related optimal and suboptimal, but acceptable, scan trajectories. The envelopes associated with two different starting points may include common trajectory points. A trainee may be allowed to select one of many possible starting positions, by a training system, after which the training system may seek to teach the trainee to guide the wand within an extended trajectory envelope representing optimal and/or suboptimal, but acceptable, trajectories associated with a starting point. The volume of the trajectory envelope may decrease, over the course of training of a particular trainee, as the trainee gains proficiency, with the trajectories contained in trajectory envelope increasing dominated by optimal trajectories.

Another perspective on the training of technicians to operate oral-cavity-imaging-and-modeling equipment is next provided. As discussed above with reference to Figure 5J, a particular scan trajectory $\mathbf{U}$ is an ordered set of points in $\mathbb{R}^7$:

$$\mathbf{U} = [\mathbf{u}_1, \mathbf{u}_2, \mathbf{u}_3, \ldots, \mathbf{u}_n]$$

$$\text{where} \quad \mathbf{u}_i = \begin{bmatrix} t_i \\ x_i \\ y_i \\ z_i \\ \theta_i \\ \varphi_i \\ \psi_i \end{bmatrix}.$$

The set of all possible trajectories $\mathbf{V}$ includes all possible scanning trajectories:

$$\mathbf{V} = [\mathbf{U}_1, \mathbf{U}_2, \ldots \mathbf{U}_n].$$

$\mathbf{V}$ is essentially an infinite set. There is a set of all possible scan trajectories that produce acceptably accurate three-dimensional oral-cavity models, $\mathbf{V}_a$:

$$\mathbf{V}_a \subset \mathbf{V}.$$

There is an additional set of all possible optimal scan trajectories $\mathbf{V}_o$:

$$\mathbf{V}_o \subset \mathbf{V}_a.$$

The set $\mathbf{V}_o$ represents a selection of trajectories from the set $\mathbf{V}_a$ via an optimization technique:

$$\mathbf{V}_o = \text{optimize}(\mathbf{V}_a, \text{constraint\_1}, \text{constraint\_2}, \ldots)$$

where a given constraint_i may be:

minimize total scan time T;
minimize number of captured images N;
minimize length at trajectory L;
minimize contact of endoscope with patient P;
minimize total rotational movement of endoscope M.

There are many different types of constraints that may be used to guide optimization, including those mentioned in the above equation. The set of constraints employed may themselves be determined by a higher-level optimization technique. A minimal goal for automated or semi-automated training of oral-cavity-imaging-and-modeling-equipment technicians is to train the technicians to carry out scans with trajectories

that fall within the set $\mathbf{V}_a$. In other words, a minimal goal of training is to ensure that technicians carry out scans that produce acceptably precise three-dimensional digital models of the oral cavities of patients. The accuracy of a three-dimensional model may be specified in many different ways, including an average discrepancy between the positions of points on the surfaces of the three-dimensional model and corresponding points on the surfaces of teeth and gums or a model of teeth and gums. A maximum goal for automated or semi-automated training may be to train technicians to carry out scans with trajectories in $\mathbf{V}_o$. The trajectory envelopes associated with a particular training subject and associated three-dimensional, digital model may be computed in advance of training or may be computed dynamically for current and predicted wand positions and orientations as a training scan proceeds.

Figure 6 provides a general architectural diagram for various types of computers. The computer system contains one or multiple central processing units ("CPUs") 602-605, one or more electronic memories 608 interconnected with the CPUs by a CPU/memory-subsystem bus 610 or multiple busses, a first bridge 612 that interconnects the CPU/memory-subsystem bus 610 with additional busses 614 and 616, or other types of high-speed interconnection media, including multiple, high-speed serial interconnects. These busses or serial interconnections, in turn, connect the CPUs and memory with specialized processors, such as a graphics processor 618, and with one or more additional bridges 620, which are interconnected with high-speed serial links or with multiple controllers 622-627, such as controller 627, that provide access to various different types of mass-storage devices 628, electronic displays, input devices, and other such components, subcomponents, and computational resources. It should be noted that computer-readable data-storage devices include optical and electromagnetic disks, electronic memories, and other physical data-storage devices. Those familiar with modern science and technology appreciate that electromagnetic radiation and propagating signals do not store data for subsequent retrieval, and can transiently "store" only a byte or less of information per mile, far less information than needed to encode even the simplest of routines. The computing subsystem within an oral-cavity-imaging-and-modeling system generally has an architecture similar to the computer architecture illustrated in Figure 6, although a large variety of different detailed computer systems may be used in

various different implementations of an oral-cavity-imaging-and-modeling system. There are many different types of computer-system architectures that differ from one another in the number of different memories, including different types of hierarchical cache memories, the number of processors and the connectivity of the processors with other system components, the number of internal communications busses and serial links, and in many other ways. However, computer systems generally execute stored programs by fetching instructions from memory and executing the instructions in one or more processors.

Figure 7A illustrates generalized hardware and software components of a general-purpose computer system, such as a general-purpose computer system having an architecture similar to that shown in Figure 6. The computer system 700 is often considered to include three fundamental layers: (1) a hardware layer or level 702; (2) an operating-system layer or level 704; and (3) an application-program layer or level 706. The hardware layer 702 includes one or more processors 708, system memory 710, various different types of input-output ("I/O") devices 710 and 712, and mass-storage devices 714. Of course, the hardware level also includes many other components, including power supplies, internal communications links and busses, specialized integrated circuits, many different types of processor-controlled or microprocessor-controlled peripheral devices and controllers, and many other components. The operating system 704 interfaces to the hardware level 702 through a low-level operating system and hardware interface 716 generally comprising a set of non-privileged computer instructions 718, a set of privileged computer instructions 720, a set of non-privileged registers and memory addresses 722, and a set of privileged registers and memory addresses 724. In general, the operating system exposes non-privileged instructions, non-privileged registers, and non-privileged memory addresses 726 and a system-call interface 728 as an operating-system interface 730 to application programs732-736 that execute within an execution environment provided to the application programs by the operating system. The operating system, alone, accesses the privileged instructions, privileged registers, and privileged memory addresses. By reserving access to privileged instructions, privileged registers, and privileged memory addresses, the operating system can ensure that application programs and other higher-level computational entities cannot

interfere with one another's execution and cannot change the overall state of the computer system in ways that could deleteriously impact system operation. The operating system includes many internal components and modules, including a scheduler 742, memory management 744, a file system 746, device drivers 748, and many other components and modules. To a certain degree, modern operating systems provide numerous levels of abstraction above the hardware level, including virtual memory, which provides to each application program and other computational entities a separate, large, linear memory-address space that is mapped by the operating system to various electronic memories and mass-storage devices. The scheduler orchestrates interleaved execution of various different application programs and higher-level computational entities, providing to each application program a virtual, stand-alone system devoted entirely to the application program. From the application program's standpoint, the application program executes continuously without concern for the need to share processor resources and other system resources with other application programs and higher-level computational entities. The device drivers abstract details of hardware-component operation, allowing application programs to employ the system-call interface for transmitting and receiving data to and from communications networks, mass-storage devices, and other I/O devices and subsystems. The file system 736 facilitates abstraction of mass-storage-device and memory resources as a high-level, easy-to-access, file-system interface. Thus, the development and evolution of the operating system has resulted in the generation of a type of multi-faceted virtual execution environment for application programs and other higher-level computational entities.

Figure 7B illustrates generalized hardware and software components of a general-purpose computer system, such as a general-purpose computer system having an architecture similar to that shown in Figure 6, which includes a virtualization layer. The computer system 750 in Figure 7B includes the same hardware layer 752 as the hardware layer 702 shown in Figure 7A. However, rather than providing an operating system layer directly above the hardware layer, as in Figure 7A, the virtualized computing environment illustrated in Figure 7B features a virtualization layer 754 that interfaces through a virtualization-layer/hardware-layer interface 756, equivalent to interface 716 in Figure 7A, to the hardware. The

virtualization layer provides a hardware-like interface 758 to a number of virtual machines, such as virtual machine 760, executing above the virtualization layer in a virtual-machine layer 762. Each virtual machine includes one or more application programs or other higher-level computational entities packaged together with an operating system, referred to as a "guest operating system," such as application 764 and guest operating system 766 packaged together within virtual machine 760. Each virtual machine is thus equivalent to the operating-system layer 704 and application-program layer 706 in the general-purpose computer system shown in Figure 7A. Each guest operating system within a virtual machine interfaces to the virtualization-layer interface 758 rather than to the actual hardware interface 756. The virtualization layer partitions hardware resources into abstract virtual-hardware layers to which each guest operating system within a virtual machine interfaces. The guest operating systems within the virtual machines, in general, are unaware of the virtualization layer and operate as if they were directly accessing a true hardware interface. The virtualization layer ensures that each of the virtual machines currently executing within the virtual environment receive a fair allocation of underlying hardware resources and that all virtual machines receive sufficient resources to progress in execution. The virtualization layer includes a virtual-machine-monitor module 768 ("VMM") that virtualizes physical processors in the hardware layer to create virtual processors on which each of the virtual machines executes. For execution efficiency, the virtualization layer attempts to allow virtual machines to directly execute non-privileged instructions and to directly access non-privileged registers and memory. However, when the guest operating system within a virtual machine accesses virtual privileged instructions, virtual privileged registers, and virtual privileged memory through the virtualization-layer interface 758, the accesses result in execution of virtualization-layer code to simulate or emulate the privileged resources. The virtualization layer additionally includes a kernel module 770 that manages memory, communications, and data-storage machine resources on behalf of executing virtual machines ("VM kernel").

Figure 8 illustrates the image-capture subsystem of one implementation of an oral-cavity-imaging-and-modeling system. The image-capture subsystem 800 includes the endoscope or wand 802, relay optics 804 that transmit

polarized laser light to the endoscope and transmit reflected light from teeth and tissues captured by the endoscope to upstream imaging components. The endoscope 802, or wand, is manipulated by the technician in order to scan oral cavities of patients and is connected, via an electro-optical cable, to the remaining components of the image-capture subsystem 800. The image-capturing subsystem 800 is interconnected with the computational system, described above with reference to Figures 6 and 7A-B, through a control interface 806, with high-speed serial or parallel signal paths 808 that are connected via a bridge to processors and memory of the computational system within the oral-cavity-imaging-and-modeling system.

The image-capture subsystem 800 includes an illumination-source subsystem 810, an image-capture-optics subsystem 820, and a main-optics subsystem 830. The illumination-source subsystem 810 includes a semiconductor laser light source 812, a polarizer 814 that polarizes the laser light emitted from the semiconductor laser 812, an optic expander 816 which alters the numerical aperture of the polarized light emitted from the polarizer 814, and a grating or micro lens array 817 that splits light input to the grating or micro lens array into multiple output light paths 818 and 819. The main-optics subsystem 830 includes a partially transparent mirror 832 which transmits light from light path 819 towards the remaining components of the main-optic subsystem 830 but which reflects light returning from the endoscope downward to the image-detection subsystem 820. The main-optics subsystem 830 further includes confocal optics 834 operating in a telecentric mode, which ameliorates distance-introduced magnification changes.

The endoscope 802 is a generally hollow wand-shaped device with an internal light transmission path and directs polarized laser light towards teeth and tissue 840. Light reflected back from teeth and tissues forms a return light beam that is passed, by the endoscope, back through the relay optics 804 and confocal optics 834 to the partially reflective mirror 832, which reflects the returning light beam into the image-capture-optics subsystem 820. The image-capture-optics subsystem includes a second polarizer 821 with a plane of polarization oriented normal to the plane of polarization of the first polarizer 814. Return light then passes through imaging optics 822 and through a matrix of pinholes 823, following which the return light falls on a charge-coupled-detector ("CCD") camera 824 for image capture. A

control module 825 controls both operation of a semiconductor laser 812 as well as a motor 826 linked to the telecentric confocal optics module 834 which is controlled to change the relative location of the focal plane of the telecentric confocal optics module with respect to the direction normal to the light-gathering aperture of the endoscope, represented by arrow 842.

The matrix, control module, and motor cooperate to monitor the intensity of individual light paths emerging from the matrix as the position of the plane of focus changes in order to determine the depth, in the direction 842, of the nearest surface of tooth or tissue to the wand. In this fashion, the wand not only captures two-dimensional images of the oral cavity, but the system, as a whole, is able to assign a distance from the wand to points in the two-dimensional image corresponding to light paths emerging from the matrix, thus producing a three-dimensional surface image, as described above with reference to Figures E-G. Both two-dimensional photograph images and three-dimensional surface images can be used alone, or together, to construct a three-dimensional digital model of the oral cavity from the two-dimensional photographic and three-dimensional surface images captured by the oral-cavity-imaging-and-modeling system.

Figure 9 illustrates image capture by the oral-cavity-imaging-and-modeling system over a small portion of a scan trajectory. In Figure 9, line 902 represents a small portion of a scan trajectory and each rectangle, such as rectangle 904, represents a captured image. As the wand is moved along a row of teeth, the oral-cavity-imaging-and-modeling system continuously monitors the time, position, and orientation of the wand and, from the information collected by monitoring, computes a variety of different parameters that the oral-cavity-imaging-and-modeling system uses to determine when to next capture and record a two-dimensional photographic and/or three-dimensional surface image. Examples of these parameters include the elapsed time since a previous image was captured, an estimated distance that the wand has moved since the last image was captured, a computed overlap between the last-captured image and an image that would be captured at the present time, the velocity of wand movement, an angular velocity of rotational movement of the wand, and many other such parameters. Values for the parameters may be estimated from previously gathered information or from received output from various

types of sensors within the wand or other components of the oral-cavity monitory system. As shown in Figure 9, the distance, in seven-dimensional space, between trajectory points at which images are captured may vary, depending on the nature of the oral-cavity features currently being imaged as well as on additional considerations. When the trajectory of the wand does not fall within the set of trajectories $\mathbf{V}_a$ that provide for generating acceptable three-dimensional digital models of the oral cavity, the oral-cavity-imaging-and-modeling system is generally unable to acquire sufficient imaging coverage of the oral cavity to allow for accurate computation of a three-dimensional digital model from the set of two-dimensional images captured by the wand as it moves along the trajectory. As one example, there may be a minimum latency time between image-capture events, as a result of which, when the wand is moving too quickly, the oral-cavity-imaging-and-modeling system is unable to acquire sufficient information for a portion of the oral cavity to construct an accurate three-dimensional digital model of that portion of the oral cavity. As another example, it may be necessary for the wand to be rotated as the wand is moved spatially along a row of teeth in order to obtain images of all portions of the teeth, and, when the wand trajectory does not include sufficient rotational motion, only a portion of the teeth are imaged, as a result of which there is insufficient information to construct an accurate three-dimensional digital model.

Figure 10 illustrates generation of an accurate three-dimensional digital model from two-dimensional images. As shown in Figure 10, when the wand is correctly employed by a technician, the trajectory of the wand, represented, in part, by dashed lines 1002 and 1004, allows for acquisition of a sufficient number and type of two-dimensional photographic and/or three-dimensional surface images to allow for generation of an accurate three-dimensional digital model 1006. By computationally overlapping the images and rotating the images with respect to one another in order to obtain maximum correspondence between features of adjacent images, a precise, digital spatial model of teeth and underlying tissue, similar to spatial models generated by various types of computer-aided-design and solid-modeling software used for mechanical systems, is obtained.

Figures 11A-B illustrate use of two-dimensional images to generate a three-dimensional model of an imaged object. In Figure 11A, a rectangular solid

object with a shaded top portion 1102 is shown. Dashed lines 1104-1106 that begin at a central point 1108 within the interior of the object and each pass through an additional point 1110-1112 on the surface of the object, indicate the directions normal to an image-capture apparatus that captures three two-dimensional images 1114-1116 of the object. From these images, as well as distance information associated with various points within the images, a partial three-dimensional model of the object 1118 can be computationally generated. Note, however, that the three-dimensional model 1118 is incomplete, having accurate representations of only three 1120-1122 of the six faces of the object. No image was taken that included portions of the other three faces. By contrast, as shown in Figure 11B, when a sufficient number of two-dimensional images, with associated depth information, are captured from a sufficient number of different directions, an accurate three-dimensional model of the object 1124 can be computationally generated. Similar considerations apply when combining two-dimensional photographic images with three-dimensional surface images and when combining three-dimensional surface images.

Figures 12A-B illustrate the need for adequate sampling frequency over spatial dimensions. In Figure 12A, a long, rectangular, solid object 1202 is imaged by an image-capture system. The image-capture system captures a first two-dimensional image 1204 from a position represented by point 1206 and direction represented by dashed line 1208 and a second two-dimensional image 1210 from a second position 1212 and direction 1214. One possible computational combination of these two two-dimensional images 1204 and 1210 would produce a partial model 1216 that includes only a portion of the front face of the long, rectangular solid object 1202. Clearly, an insufficient amount of information is contained in the two two-dimensional images 1204 and 1210 to reconstruct even an accurate representation of one face of the long, rectangular solid object 1202. By contrast, as shown in Figure 12B, when a sufficient number of images are acquired along a direction parallel to the long axis of the solid-rectangular object 1220-1226, then, by computationally computing translational overlaps of adjacent images, a final accurate model of the front face of the solid-rectangular object 1230 can be produced. Thus, for accurate three-dimensional digital modeling, two-dimensional images need to be captured from a sufficient number of orientations and translational positions to provide

sufficient coverage of the surfaces and features of the three-dimensional object in order to computationally reconstruct the three-dimensional object from the collected two-dimensional images and depth information. Similar considerations apply when combining two-dimensional photographic images with three-dimensional surface images and when combining three-dimensional surface images.

When an accurate three-dimensional digital model of the oral cavity of a particular patient is known, or when, for training purposes, a technician employs an oral-cavity-imaging-and-modeling system to image and generate a three-dimensional model for a physical model already associated with an accurate three-dimensional digital model, information collected by a wand can be used to determine the spatial position and rotational orientation of the wand.

Figure 13 shows a particular image-capture event with respect to a row of teeth and underlying tissue. The captured image, represented by rectangle 1302, has a particular distance in a normal direction, represented by dashed arrow 1304, from each point on the imaged surfaces of the row of teeth. In Figure 13, a particular point 1306 on the surface of a tooth is nearest to a central point 1308 of the two-dimensional image 1302 in the normal direction 1304. When there is an already generated, accurate three-dimensional digital model for the row of teeth being imaged, as shown in Figure 13, a two-dimensional photographic or three-dimensional surface image captured from a wand at a particular spatial and rotational position can be used to determine the spatial and rotational position of the wand. The two-dimensional photographic or three-dimensional surface image can be matched to a plane projection of a portion of the three-dimensional digital model by translations and rotations of the two-dimensional image with respect to the three-dimensional digital model. The translations and rotations that place the two-dimensional photographic or three-dimensional surface image in a position corresponding to the best-matching plane projection can be used to compute the spatial position and rotational orientation of the wand.

Figures 14A-B illustrate determination of a trajectory point corresponding to a two-dimensional photographic or three-dimensional surface image captured during a training session. By a search of possible spatial and rotational orientations of the two-dimensional image with respect to the three-dimensional

model, a best-matching position and orientation is found. As shown in Figure 14A, the position and orientation can be expressed as a set of three angles 1402-1404 with respect to a model coordinate system and a local or relative position of an origin 1406 of a local Cartesian coordinate system in terms of an absolute Cartesian coordinate system used for the model. In Figure 14A, dashed arrow 1408 has the same length and direction as the dashed arrow 1304 in Figure 13. As shown in Figure 14B, this information, along with an indication of the time that the two-dimensional image was captured, *t*, allows for the computation of a seven-dimensional vector representing a trajectory point 1408 for the wand or endoscope, as discussed above with reference to Figure 5F. Thus, when a trainee scans a particular patient or physical model with which an accurate three-dimensional digital model is already associated, the images captured during this scan can be used to determine the trajectory of the wand during a training scam. The ability to determine the trajectory of the wand during a training session provides the foundation for automated and semi-automated training subsystems that can be incorporated into an oral-cavity-imaging-and-modeling system.

Figures 15A-G illustrate one example user interface for an automated or semi-automated training system that trains technicians to efficiently and accurately scan oral cavities using oral-cavity-imaging-and-modeling systems. The user interface is displayed on the display screen of the oral-cavity-imaging-and-modeling system as well as, in certain implementations, on display screens of remote computer systems to allow remote training supervisors to follow a training session. In alternative implementations, a local computer system connected with the oral-cavity-imaging-and-modeling system is used both to display the training user interface as well as to carry out computing tasks associated with training. The user interface 1500 includes a training-scan-indication window 1502, a real-time-position window 1504, graphical indications of needed spatial 1506 and orientation 1508-1510 changes in the spatial position and orientation of the wand, an elapsed-time indication 1512, and a model window 1514. These features are described, below, with reference to Figures 15B-G that show a sequence of information displays during a training session.

Figure 15B shows an initial information display, when a trainee has activated the wand and is attempting to position the wand to initiate a scan. The training-scan-indication window 1502 uses a curved arrow or other graphical indication 1516 to indicate to the trainee a particular scan or scan segment to next carry out during the training session. The real-time-position window 1504 displays a current wand position 1518. Because the current spatial position and rotational orientation of the wand does not coincide with a point within any trajectory envelope that would produce an acceptable three-dimensional digital model of the scanned oral cavity or oral-cavity model, the oral-cavity-imaging-and-modeling system displays graphical indications 1520-1523 of spatial translations and rotations needed to position the wand appropriately to start the scan. As shown in Figure 15C, once the technician has properly positioned and oriented the wand, as represented by position 1524, an audible or visual indication may be made to the trainee to commence scanning. In Figure 15D, the trainee has begun scanning a row of teeth or a model of a row of teeth. The spatial trajectory of the scan is indicated graphically 1526 in the real-time-position window 1504. Because the trajectory falls within the trajectory envelope of an acceptable scan, no indications are displayed for moving or rotating the wand. The elapsed-time display 1512 shows an indication of the elapsed time of the training scan 1528 as well as an indication of an optimal elapsed time 1530. In this case, the trainee has moved the wand somewhat too slowly, as a result of which the trajectory may be approaching an unacceptable trajectory or non-optimal trajectory.

Figure 15E shows the display after the scan has proceeded further. The spatial trajectory up to the current point in time is shown graphically 1532 in the real-time-position window 1504. In this case, the spatial trajectory and wand orientation have departed from either an acceptable or optimal trajectory, depending on the goals of the particular training session, as a result of which the training subsystem displays indications of spatial and rotational movements needed to return to an acceptable or optimal scan trajectory 1534-1537. The elapsed-time indicator 1512 now shows that the elapsed time for the training scan 1538 is lagging an acceptable or optimal elapsed time 1540, indicating that the trainee is now moving the wand too quickly.

Figure 15F shows the user-interface display for the training session after the trainee has completed the scan operation indicated in the training-scan-indication window 1502. The spatial trajectory of the trainee's scan is shown by a three-dimensional curve 1546 in the real-time-position window 1504. The elapsed-time indication 1512 indicates a final elapsed time 1548 for the trainee's scan which is significantly greater than an acceptable or optimal elapsed time 1550, depending on the goal of the training session. Thus, over the course of the entire scan, the trainee moved the wand too quickly.

Figure 15G shows a final display of the training user interface following completion of the scan indicated in the training-scan-indication window 1502. The model window 1514 now displays the three-dimensional digital model generated from information collected during the training scan. Those portions that have been accurately determined are shown in solid lines, such as tooth 1552, while the portions that have failed to have been generated from the scan are shown in dashed lines, such as tooth 1554. In addition, the user interface may display any number of different metrics for the training session, such as indications of the percent of coverage of the generated three-dimensional model, indications of the degree of departure of the scan trajectory from an acceptable or optimal scan, depending on the goal of the training session, and much additional information. For example, the graphical indication of the spatial trajectory of the training scan 1546 may be annotated with points, such as point 1556, where images were captured. This can be correlated with a previously generated accurate three-dimensional digital model to determine those portions of the scan trajectory which were unacceptable or non-optimal and in which insufficient images were captured for generating the three-dimensional digital model.

Figure 16 illustrates use of one implementation of the automated or semi-automated training system that trains technicians to efficiently and accurately scan oral cavities using oral-cavity-imaging-and-modeling systems. As shown in Figure 16, the trainee 1602 scans a patient 1604 for whom an accurate three-dimensional digital oral-cavity model has been previously prepared and stored in the oral-cavity-imaging-and-modeling system 1606. As the trainee carries out an indicated scan, the trainee can watch the training user interface 1608 displayed on the

display device 1610 of the oral-cavity-imaging-and-modeling system. A remote training supervisor 1612 can follow the same displayed information 1614 on a remote computer system 1616 connected to the oral-cavity-imaging-and-modeling system 1606. In addition, the training supervisor may receive a video of the trainee and patient on a separate display device or in an additional display window in order to observe the trainee's actions during the training session. The trainee and training supervisor may additionally communicate over an audio connection or by audio-visual communications. All of the information collected during training sessions may be digitally stored and subsequently retrieved for review and for monitoring a trainee's progress over multiple training sessions. In certain implementations, multiple training supervisors interact with multiple, geographically distinct computer systems to observe and participate in training sessions.

Figure 17 illustrates two different data structures that are maintained by the training subsystem of an oral-cavity-imaging-and-modeling system during training sessions to facilitate the calculation and display of information by a training user interface and for other training purposes. A first array 1702 stores trajectory points, discussed above with reference to Figure 5F. In certain implementations, the trajectory points are encoded as vectors in a seven-dimensional vector space, with elements corresponding to time, spatial coordinates, and rotational angles. The trajectory points are computed, as discussed above with reference to Figures 13-14B, from images captured during training scans. The trajectory points are sorted in time-of-capture order. Various cells of the array can be marked to indicate the starting points and ending points of scans and subscans 1706-1709. A second array 1712 stores captured images obtained during a training scan by the oral-cavity-imaging-and-modeling system. These captured images are annotated with the time of capture, such as time value 1714 associated with captured image 1716. In certain cases, every image captured during a training scan may be stored in the array. In other implementations, the images are stored only long enough to compute trajectory points from the images, except in the case of images that also correspond to an image that would have been captured and stored during a regular scan by the oral-cavity-imaging-and-modeling system. These latter images are used to continuously construct a training-session three-dimensional model from the images captured

during the training scan. The training-session three-dimensional model can be compared to an accurate, previously generated three-dimensional model for the particular patient or a physical model that is the subject of the training session in order to determine metrics for the accuracy and completeness of the training-session three-dimensional model. The data stored in the two arrays 1702 and 1712 forms the basis for information and feedback provided by an automated or semi-automated training system.

Figures 18A-H provide control-flow diagrams that illustrate implementation of one example automated training subsystem incorporated within an oral-cavity-imaging-and-modeling system for training oral-cavity-imaging-and-modeling-system technicians to efficiently and accurately scan patients. Figure 18A shows a training-subsystem event loop that continuously runs in order to handle all of the various types of events that occur during a training system. This event loop lies at the lowest level of a training-subsystem control program. The training-subsystem control program interfaces to an operating system or guest operating system within the oral-cavity-imaging-and-modeling system which includes a lower-level event loop for handling the various types of hardware events that occur during operation of an oral-cavity-imaging-and-modeling system. In step 1802, the event loop waits for a next event. Then, in a series of conditional steps, the type of next-occurring event is determined and an appropriate handler called for the event. For example, events may include scan-timer expirations, detected in step 1804 and handled by a call to a scan-timer-expiration handler 1806. Other events include wand control input, detected in step 1808, wand image input, detected in step 1810, expiration of a training timer, detected in step 1812, and user input to a keyboard, touch screen, voice-activated subsystem, or other input device, detected in step 1814.

Figure 18B illustrates one of the handlers called from conditional statements in the event loop illustrated in Figure 18A. Figure 18B illustrates the user-input handler called in step 1816 of Figure 18A. In step 1818, the user-input handler determines the input feature or particular device feature from which the input was received and any thread associated with that input feature to notify that an input event has occurred. In step 1819, the user-input handler receives the input and buffers the input. When there is a thread associated with the input feature, as determined in step

1820, then, in step 1821, the user-input handler notifies the thread and passes the input stored in the input buffer to the thread. Otherwise, in step 1822, the user-input handler launches an appropriate thread for unregistered input and passes the input buffer to the thread as initial input to the thread.

Figures 18C-D illustrate a training thread that is invoked by user input to an input feature that launches the training thread. In step 1824, the training thread displays a trainee-information-input screen to collect information from the trainee. In step 1825, the training thread sets a timer and waits for input to be received. When input is not received after timer expiration, as determined in step 1826, error handling is undertaken in step 1827, after which the training thread terminates or trainee-information-input screen is again displayed, as determined in step 1828. When trainee information is received, in step 1829, the trainee information is used to access stored information for the trainee, and perhaps supplement the stored information, in order to determine a training plan for the current training session along with associated training-plan parameters. When there is a remote training console for the training session, as determined in step 1830, the training thread initializes communications with remote console, in step 1831, and displays the training panel, or training user interface, to the remote console display in step 1832. In step 1833, the training thread displays the training panel to the local display on the oral-cavity-imaging-and-modeling system and registers the training thread to receive wand inputs and other types of events associated with the scanning operation. It is assumed that, when a remote training panel has been displayed, all subsequent output to the training panel is transmitted to both the locally displayed and remotely displayed training panel. In step 1834, the second part of the training thread, shown in Figure 18D, is invoked.

A training session may include numerous subscans that together constitute a single training scan. The number and types of subscans are encoded in the training-plan parameters determined in step 1829. In the *for*-loop of steps 1835-1839 of Figure 18D, the training thread carries out a training subscan for each subscan in the training plan. Each subscan involves initial positioning, carried out in step 1836, monitoring of the subscan, carried out in step 1837, and clearing of a training timer following completion of the subscan in step 1838. After the subscans

are completed, a training-session three-dimensional digital model is computed from those images captured during the training scan that would have been captured during a normal scanning procedure and displayed in the model window of the user input to the trainee, in step 1840. Additional training plan results and metrics may be computed and displayed to the trainee in step 1842. As discussed above, all of the displayed information, including the generated three-dimensional digital model and results provide various types of feedback to the trainee to indicate how well the trainee accomplished the goal of the current training session. These metrics may include degree of coverage, degree of completion of the three-dimensional digital model, degree of accuracy of the three-dimensional digital model, suggestions for improving efficiency and accuracy in the trainee's scanning techniques, and many other types of information. The training model may be continuously displayed, as it is being constructed, displayed after completion of a training subscan, or displayed after the completion of a training scan.

Figure 18E provides a control-flow diagram for the initial-positioning step 1836 in Figure 18D. In step 1844, the initial-positioning routine initializes the arrays, discussed above with reference to Figure 17, for storing trajectory points, or time/position/orientation vectors, and the array of snapshots. Then, in step 1845, the initial-positioning routine displays an indication of the subscan to be carried out, in the training-scan-indication window of the user interface, sets a Boolean variable *positioning* to TRUE, starts a training timer, and displays or produces an indication to the trainee to begin a subscan. In step 1846, the initial-positioning routine waits for wand input to indicate that the trainee has begun to position the wand for initiation of the scan. During this time, images are being captured and trajectory points computed from those images, from which the spatial position and rotational orientation of the wand is computed, along with various other types of computed values, such as the spatial velocity and rotational velocity of the wand. When the current position of the wand is acceptable, as determined in step 1847, the Boolean variable *positioning* is set to false and the start point for the subscan is noted in the trajectory-point array, in step 1848. Otherwise, the training subsystem computes and displays translational and/or rotational indications, in step 1849, to the trainee in order to direct the trainee to properly position the wand for the indicated subscan.

Figure 18F provides a control-flow diagram for the routine "subscan" invoked in step 1837 of Figure 18D. During the subscan carried out by a trainee, the routine "subscan" waits for a next event notification, in step 1850, and for each event notification, carries out an appropriate action. When the event notification is an off-course event indicating that the wand trajectory has departed from the envelope of an acceptable or optimal trajectory, as detected in step 1851, the routine "subscan" computes and displays translational and/or rotational indications to guide the trainee to return to the trajectory of an acceptable or optimal scan in step 1852. When the event is a subscan-done event, as determined in step 1853, then the routine "subscan" notes the end point in the trajectory-point array for the current subscan and returns, in step 1854. Other types of events that occur during the subscan may be handled by a default handler 1856. After handling of a particular event, the routine "subscan" either continues to wait for another event, in the case that the event is a routine non-terminating event or returns, in the case of a terminating event, such as a subscan-done event or any of various of different types of error events that may be handled by the default handler.

As the subscan is initialized and carried out by a trainee, the training timer expires and is reset at a relatively high frequency, in order for the oral-cavity-imaging-and-modeling system to rapidly capture images and compute wand positions and orientations as well as to compute derived values, such as the translational and rotational speeds of the wand. Figure 18G is a control-flow diagram for the training-timer-expiration handler, called in step 1817 of Figure 18A. When there is a new input image available from the wand, as determined in step 1860, a routine "process image" is called in step 1862 to process the image. In step 1864, the current system time is determined. When the current system time indicates that it is time to initiate a new image capture, as determined in step 1865, capture of a new image by the wand is initiated in step 1866. When an image would be captured by the oral-cavity-imaging-and-modeling system during a regular scan at the current point in time, based on the trajectory of the wand and other considerations, as determined in step 1867, a position in the snapshot array is marked as a regular-scan image, in step 1868. This may be the position of the most recently captured image or the position at which the next-captured image will be stored in the array. When the current position of the

wand has strayed outside of the envelope of an acceptable or optimal wand trajectory, depending on the goal of the training session, as determined in step 1869, then, in step 1870, the training-timer-expiration handler notifies the training thread of an off-course event. When the current position represents the end of a subscan, as determined in step 1871, the training-timer-expiration handler notifies the training thread of a subscan-done event, in step 1872. When the wand has been inactive for some threshold amount of time, as determined in step 1873, the training-timer-expiration handler also notifies the training thread that a subscan-done event has occurred. Otherwise, the training-timer-expiration handler resets the training timer in step 1874. When the current time indicates that it is time to update the elapsed-time indicator, as determined in step 1875, the elapsed-time indicator is updated in step 1876. When the current system time indicates that it is time to update the real-time-position, or trajectory display, as determined in step 1877, then when initial positioning is occurring, as determined in step 1878, the current position of the wand is displayed in step 1879. Otherwise, during a training scan or subscan, the current position is added to a displayed spatial trajectory in step 1880.

Figure 18H provides a control-flow diagram for the routine "process image" called in step 1862 of Figure 18G. In step 1890, the routine "process image" rotates and translates the newly captured image with respect to the three-dimensional digital model previously obtained for the patient or model that is being scanned in the training session in order to best match the image to a projection from a particular position on the surface of the model, as discussed above with reference to Figures 13-14B. Then, in step 1891, the routine "process image" computes the position and orientation of the wand based on the rotations and translations needed to match the image with a projection from the three-dimensional digital model. The position, orientation, and time are saved as a vector in the trajectory-point array in step 1892. When there are sufficient vectors stored in the array to determine the velocities of the wand, as determined in step 1893, the velocities of the wand are computed in step 1894 from stored trajectory points over some preceding time window. Velocities may include a spatial velocity as well as three different rotational velocities. Finally, in step 1895, the image is stored in the image array along with the time. In certain embodiments, only those images that correspond to images that would have been

captured by the oral-cavity-imaging-and-modeling system during an actual scan may be stored while in other implementations, those images are marked as normal-scan images but all of the captured images are maintained in the array.

Although the present invention has been described in terms of particular embodiments, it is not intended that the invention be limited to these embodiments. Modifications within the spirit of the invention will be apparent to those skilled in the art. For example, any of many different types of absolute or relative coordinate systems can be used for expressing spatial and rotational coordinates for the wand with respect to an imaged object during normal scans and training scans. Such coordinate systems may be based on Cartesian coordinate systems, various types of curve or linear coordinate systems, or groups of mathematically related coordinate systems. Many different types of user-interface displays may be provided to trainees during training sessions and may present many additional and different types of visual queues, visual information, and results and suggestions. In various implementations, the user interface may be displayed on a personal computer connected to the oral-cavity-imaging-and-modeling system rather than on the display of the oral-cavity-imaging-and-modeling system. The three-dimensional digital model computed based on a training scan may be continuously prepared and displayed on the user interface as the scan is carried out or, as in the described implementation, may be created following all of the subscans in a training scan. Many different implementations of an automated or semi-automated training system can be obtained by varying any of many different design and implementation parameters, including hardware platforms, display devices, programming languages, modular organizations, data structures, control structures, and many other such design and implementation parameters. Automated training systems may computationally generate all displayed results, suggestions, and user feedback while semi-automated training systems may allow a training supervisor to locally or remotely assist in guiding a trainee through audio, touch-screen, or keyboard inputs. Automated and semi-automated training systems may be partially implemented in cloud-computing-facility computers or other remote systems, including distributed systems, which receive wand position and orientation data from an oral-cavity-imaging-and-modeling system through any of various electronic communications media.

The invention provides an automated system for guiding a wand according to claim 1. Additional optional features are given by dependent claims 2 to 10, wherein the features of any dependent system claim may be combined with the features of any preceding system claim. The invention further provides a method according to claim 11. Additional optional features are given by dependent claims 12 to 19, wherein the features of any dependent method claim may be combined with the features of any preceding method claim. The invention further provides computer instructions, stored in a physical data-storage device according to claim 20. These computer instructions may be adapted to perform a method according to any of the claims 11 to 19.

Additionally, the invention provides the following embodiments:

1. An automated training system, in particular, that monitors a training scan within the oral cavity of a patient in order to display training information, comprising:

one or more processors;

one or more memories that are accessed by the one or more processors;

a display device; and

computer instructions, stored in one or more of the one or more memories that, when executed by the automated training system, control the automated training system to

display a training user interface on the display device,

continuously captures images of multiple surfaces of a three-dimensional, solid object from a wand that illuminates the one or more surfaces and receives reflected and scattered light from the one or more illuminated surfaces as the wand is moved along a trajectory to scan the one or more surfaces during a training scan,

computes and stores, in one or more of the one or more memories, an ordered set of spatial positions and orientations of the wand by matching images of the captured images to projections of a previously created three-dimensional digital model of the solid object, and

computes and displays, within the user interface on the display device, information regarding the accuracy and efficiency of the training scan from the stored ordered set of spatial positions and orientations of the wand.

2. The automated training system of embodiment 1 wherein the solid object is teeth and tissues within the oral cavity of a patient.

3. The automated training system of embodiment 1 wherein the solid object is a three-dimensional model of teeth and tissues.

4. The automated training system of embodiment 1 wherein each element of the ordered set of spatial positions and orientations of the wand includes:

three spatial coordinates;

three orientation coordinates; and

an indication of the time at which the image was captured from which the spatial coordinates and orientation coordinates were calculated.

5. The automated training system of embodiment 4 wherein the automated training system computes the spatial and orientations coordinates of an element of the ordered set of spatial positions and orientations of the wand by:

searching a space of spatial positions and orientations relative to the previously created three-dimensional digital model of the solid object in order to determine a spatial position and orientation of a captured image at which the captured image matches a projection of a portion of the surface of the previously created three-dimensional digital model of the solid object in a direction normal to the plane of the captured image; and

computing the spatial and orientations coordinates of the wand from the determined spatial position and orientation of the captured image.

6. The automated training system of embodiment 4 further comprising:

designating, as normal-scan images, those images captured during the training scan that would have been captured during a normal, non-training scan in

which the wand follows a trajectory equivalent to the trajectory of the training scan; and

computing, during or after the training scan, a training-scan-generated three-dimensional digital model of the solid object.

7. The automated training system of embodiment 6 wherein the information regarding the accuracy and efficiency of the training scan includes one or more of:

indications of the translational velocity of the wand;

indications of the rotational velocity of the wand;

indications of the elapsed time of the scan;

indications of the accuracy of the training-scan-generated three-dimensional digital model of the solid object;

indications of the degree of coverage of the normal-scan images with respect to the surface of the previously created three-dimensional digital model of the solid object;

indications of the spatial trajectory of the wand during the training scan;

indications of the points, in the spatial trajectory of the wand during the training scan, at which normal-scan images were captured;

indications of the similarity of the spatial trajectory of the wand during the training scan to an acceptable-trajectory envelope within which normal-scan images can be captured and used to construct an accurate three-dimensional digital model of the solid object; and

indications of the similarity of the spatial trajectory of the wand during the training scan to an optimal trajectory envelope within which normal-scan images can be captured and used to construct an accurate three-dimensional digital model of the solid object.

8. The automated training system of embodiment 1 wherein the user interface is additionally displayed on the display of a remote computer system.

9. The automated training system of embodiment 1 wherein a trainee interacting with the automated training system communicates with a user of the remote computer system by voice and inputs to one or more input devices.

10. The automated training system of embodiment 1 wherein a captured image is one of:

a two-dimensional photographic image; and

a three-dimensional surface image.

It is appreciated that the previous description of the disclosed embodiments is provided to enable any person skilled in the art to make or use the present disclosure. Various modifications to these embodiments will be readily apparent to those skilled in the art, and the generic principles defined herein may be applied to other embodiments without departing from the spirit or scope of the disclosure. Thus, the present disclosure is not intended to be limited to the embodiments shown herein but is to be accorded the widest scope consistent with the principles and novel features disclosed herein.

CLAIMS

1. An automated system for guiding a wand for scanning one or more surfaces of a three-dimensional, solid object, in particular, within the oral cavity of a patient, comprising:

one or more processors;

one or more memories that are accessed by the one or more processors;

a display device; and

computer instructions, stored in one or more of the one or more memories that, when executed by the automated training system, control the automated training system to

display a training user interface on the display device,

continuously captures images of multiple surfaces of a three-dimensional, solid object from a wand that illuminates the one or more surfaces and receives reflected and scattered light from the one or more illuminated surfaces as the wand is moved along a trajectory to scan the one or more surfaces during a training scan,

computes and stores, in one or more of the one or more memories, an ordered set of spatial positions and orientations of the wand by matching images of the captured images to projections of a previously created three-dimensional digital model of the solid object, and

computes and displays, within the user interface on the display device, information regarding the accuracy and efficiency of the training scan from the stored ordered set of spatial positions and orientations of the wand.

2. The automated system of claim 1 wherein the solid object is teeth and tissues within the oral cavity of a patient.

3. The automated system of claim 1 wherein the solid object is a three-dimensional model of teeth and tissues.

4. The automated system of claim 1 wherein each element of the ordered set of spatial positions and orientations of the wand includes:

three spatial coordinates;

three orientation coordinates; and

an indication of the time at which the image was captured from which the spatial coordinates and orientation coordinates were calculated.

5. The automated system of claim 4 wherein the automated system computes the spatial and orientations coordinates of an element of the ordered set of spatial positions and orientations of the wand by:

searching a space of spatial positions and orientations relative to the previously created three-dimensional digital model of the solid object in order to determine a spatial position and orientation of a captured image at which the captured image matches a projection of a portion of the surface of the previously created three-dimensional digital model of the solid object in a direction normal to the plane of the captured image; and

computing the spatial and orientations coordinates of the wand from the determined spatial position and orientation of the captured image.

6. The automated system of claim 4 further comprising:

designating, as normal-scan images, those images captured during the training scan that would have been captured during a normal, non-training scan in which the wand follows a trajectory equivalent to the trajectory of the training scan; and

computing, during or after the training scan, a training-scan-generated three-dimensional digital model of the solid object.

7. The automated system of claim 6 wherein the information regarding the accuracy and efficiency of the training scan includes one or more of:

indications of the translational velocity of the wand;

indications of the rotational velocity of the wand;

indications of the elapsed time of the scan;

indications of the accuracy of the training-scan-generated three-dimensional digital model of the solid object;

indications of the degree of coverage of the normal-scan images with respect to the surface of the previously created three-dimensional digital model of the solid object;

indications of the spatial trajectory of the wand during the training scan;

indications of the points, in the spatial trajectory of the wand during the training scan, at which normal-scan images were captured;

indications of the similarity of the spatial trajectory of the wand during the training scan to an acceptable-trajectory envelope within which normal-scan images can be captured and used to construct an accurate three-dimensional digital model of the solid object; and

indications of the similarity of the spatial trajectory of the wand during the training scan to an optimal trajectory envelope within which normal-scan images can be captured and used to construct an accurate three-dimensional digital model of the solid object.

8. The automated system of claim 1 wherein the user interface is additionally displayed on the display of a remote computer system.

9. The automated system of claim 1 wherein a trainee interacting with the automated system communicates with a user of the remote computer system by voice and inputs to one or more input devices.

10. The automated system of claim 1 wherein a captured image is one of:

a two-dimensional photographic image; and

a three-dimensional surface image.

11. A method controlled by computer instructions executed in an automated training system having one or more processors, one or more memories that are accessed by the one or more processors, and a display device, the method comprising:

continuously capturing images of multiple surfaces of a three-dimensional, solid object from a wand that illuminates the one or more surfaces and receives reflected and scattered light from the one or more illuminated surfaces as the wand is moved along a trajectory to scan the one or more surfaces during a training scan; and

computing and storing, in one or more of the one or more memories, an ordered set of spatial positions and orientations of the wand by matching images of the captured images to projections of a previously created three-dimensional digital model of the solid object.

12. The method of claim 11 wherein each element of the ordered set of spatial positions and orientations of the wand includes:

three spatial coordinates;

three orientation coordinates; and

an indication of the time at which the image was captured from which the spatial coordinates and orientation coordinates were calculated.

13. The method of claim 11 wherein computing the spatial and orientations coordinates of an element of the ordered set of spatial positions and orientations of the wand further include:

searching a space of spatial positions and orientations relative to the previously created three-dimensional digital model of the solid object in order to determine a spatial position and orientation of a captured image at which the captured image matches a projection of a portion of the surface of the previously created three-dimensional digital model of the solid object in a direction normal to the plane of the captured image; and

computing the spatial and orientations coordinates of the wand from the determined spatial position and orientation of the captured image.

14. The method of claim 13 further comprising:

designating, as normal-scan images, those images captured during the training scan that would have been captured during a normal, non-training scan in which the wand follows a trajectory equivalent to the trajectory of the training scan; and

computing, during or after the training scan, a training-scan-generated three-dimensional digital model of the solid object.

15. An method of claim 14 further comprising:

computing and displaying, on the display device, information regarding the accuracy and efficiency of the training scan from the stored ordered set of spatial positions and orientations of the wand.

16. An method of claim 15 wherein the information regarding the accuracy and efficiency of the training scan includes one or more of:

indications of the translational velocity of the wand;

indications of the rotational velocity of the wand;

indications of the elapsed time of the scan;

indications of the accuracy of the training-scan-generated three-dimensional digital model of the solid object;

indications of the degree of coverage of the normal-scan images with respect to the surface of the previously created three-dimensional digital model of the solid object;

indications of the spatial trajectory of the wand during the training scan;

indications of the points, in the spatial trajectory of the wand during the training scan, at which normal-scan images were captured;

indications of the similarity of the spatial trajectory of the wand during the training scan to an acceptable-trajectory envelope within which normal-scan images can be captured and used to construct an accurate three-dimensional digital model of the solid object; and

indications of the similarity of the spatial trajectory of the wand during the training scan to an optimal trajectory envelope within which normal-scan images can be captured and used to construct an accurate three-dimensional digital model of the solid object.

17. The method of claim 11 wherein the solid object is teeth and tissues within the oral cavity of a patient.

18. The method of claim 11 wherein the solid object is a three-dimensional model of teeth and tissues.

19. The method of claim 11 wherein a captured image is one of:

a two-dimensional photographic image; and

a three-dimensional surface image.

20. Computer instructions, stored in a physical data-storage device, that, when executed in an automated training system having one or more processors, one or more memories that are accessed by the one or more processors, and a display device, control the automated training system to:

continuously capturing images of multiple surfaces of a three-dimensional, solid object from a wand that illuminates the one or more surfaces and receives reflected and

scattered light from the one or more illuminated surfaces as the wand is moved along a trajectory to scan the one or more surfaces during a training scan; and

computing and storing, in one or more of the one or more memories, an ordered set of spatial positions and orientations of the wand by matching images of the captured images to projections of a previously created three-dimensional digital model of the solid object.

21. An automated training system comprising:

one or more processors;

one or more memories that are accessed by the one or more processors;

a display device; and

computer instructions, stored in one or more of the one or more memories that, when executed by the automated training system, control the automated training system to

display a training user interface on the display device,

continuously captures images of multiple surfaces of a three-dimensional, solid object from a wand that illuminates the one or more surfaces and receives reflected and scattered light from the one or more illuminated surfaces as the wand is moved along a trajectory to scan the one or more surfaces during a training scan,

computes and stores, in one or more of the one or more memories, an ordered set of spatial positions and orientations of the wand by matching images of the captured images to projections of a previously created three-dimensional digital model of the solid object, and

computes and displays, within the user interface on the display device, information regarding the accuracy and efficiency of the training scan from the stored ordered set of spatial positions and orientations of the wand.

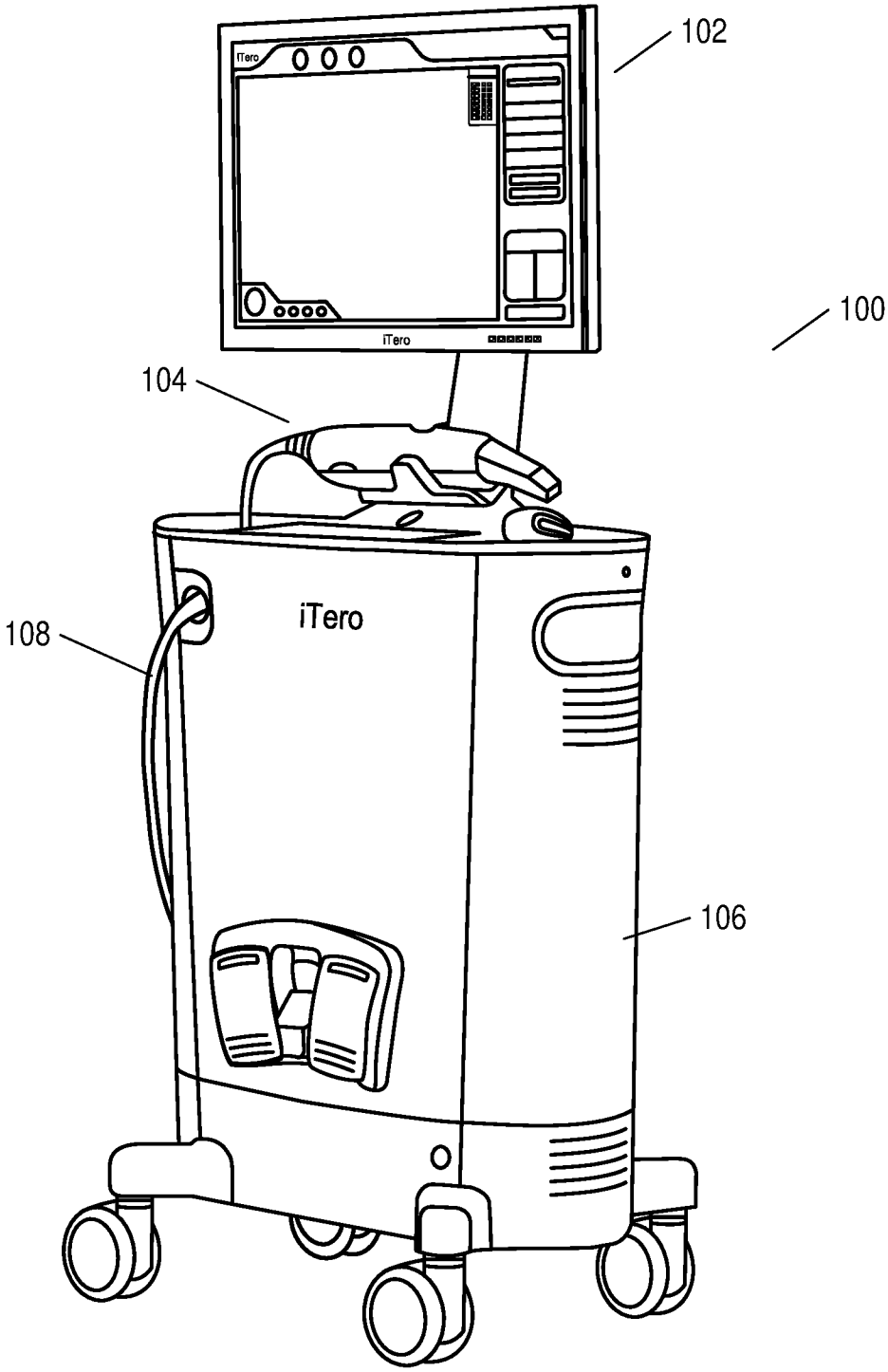

FIG. 1

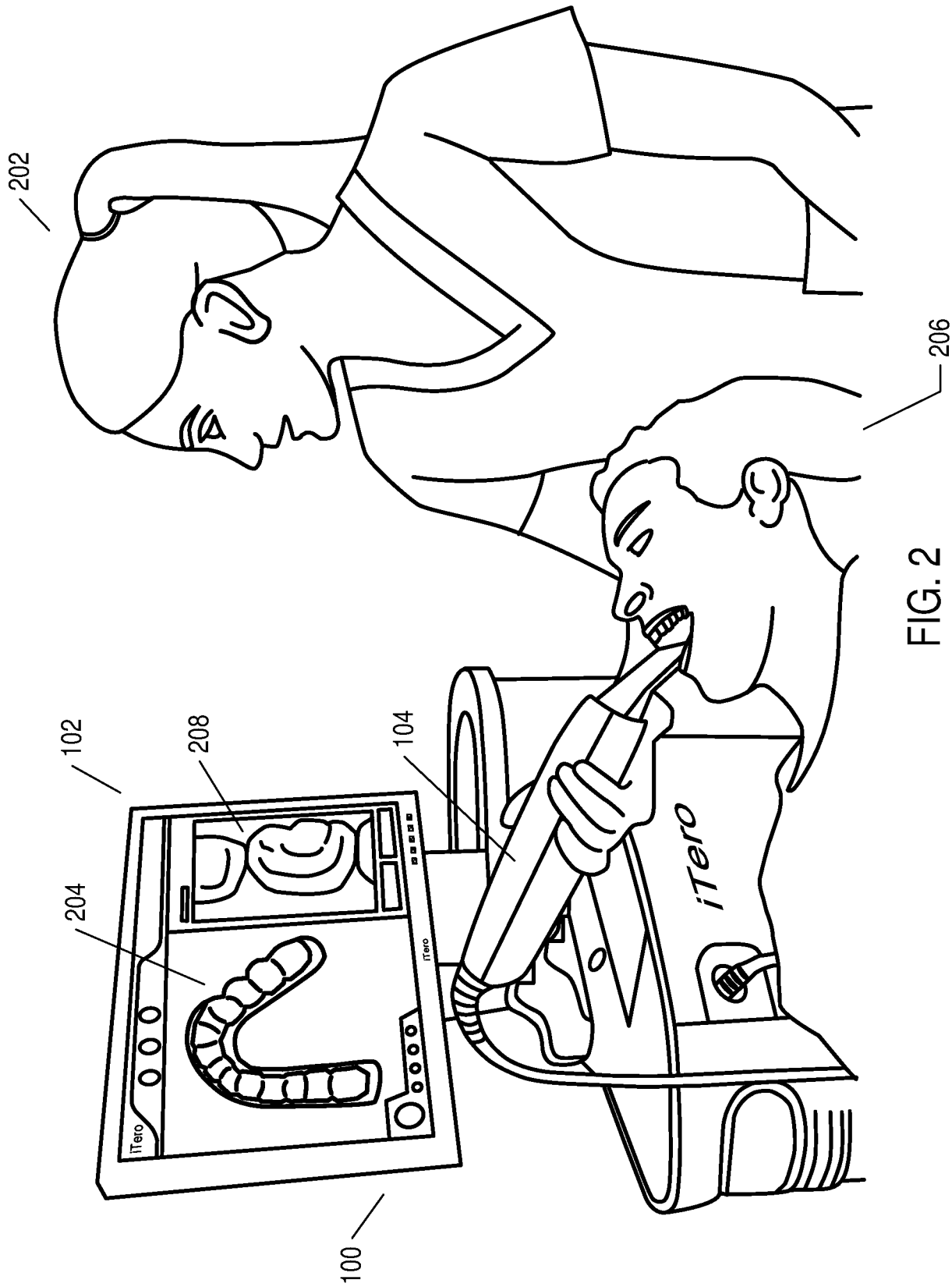

FIG. 2

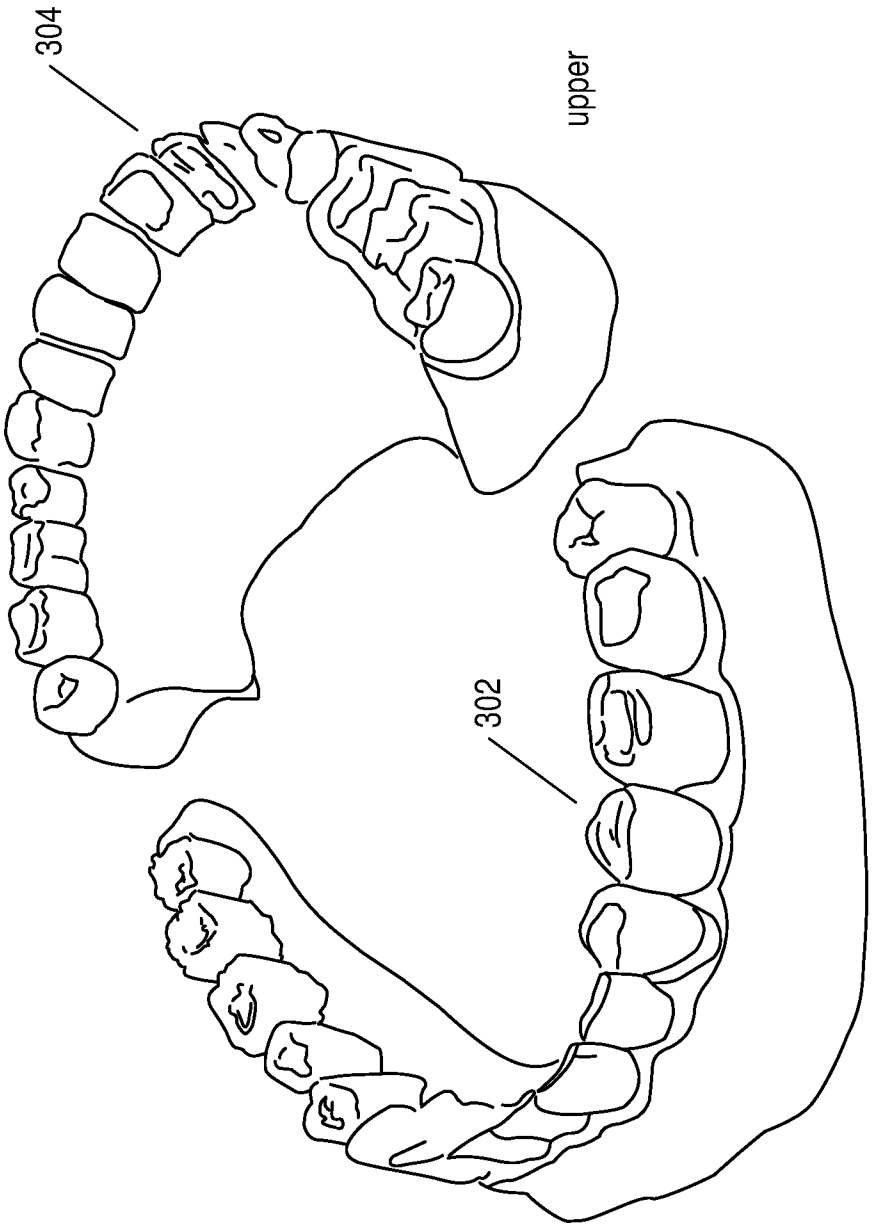

FIG. 3

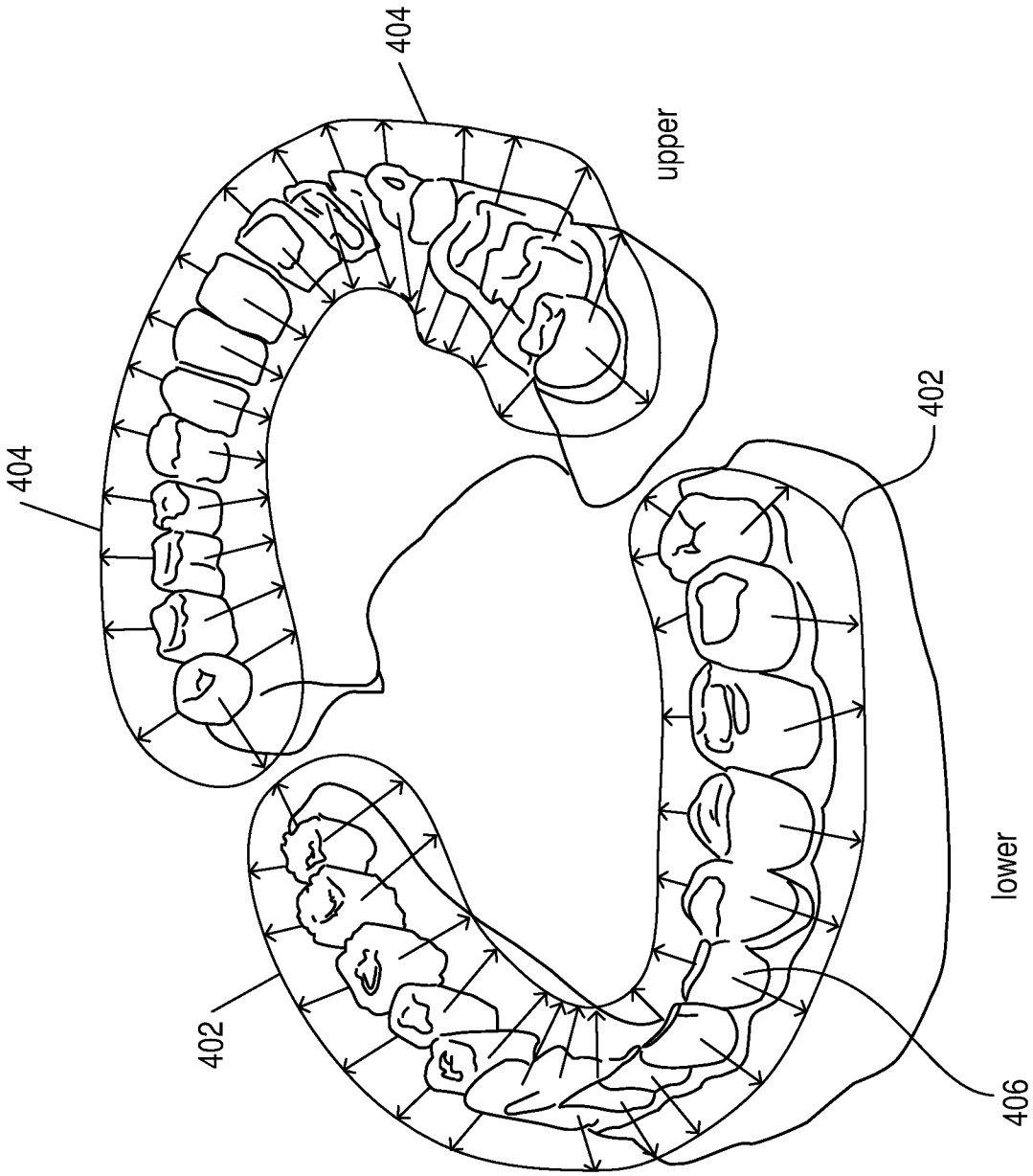

FIG. 4

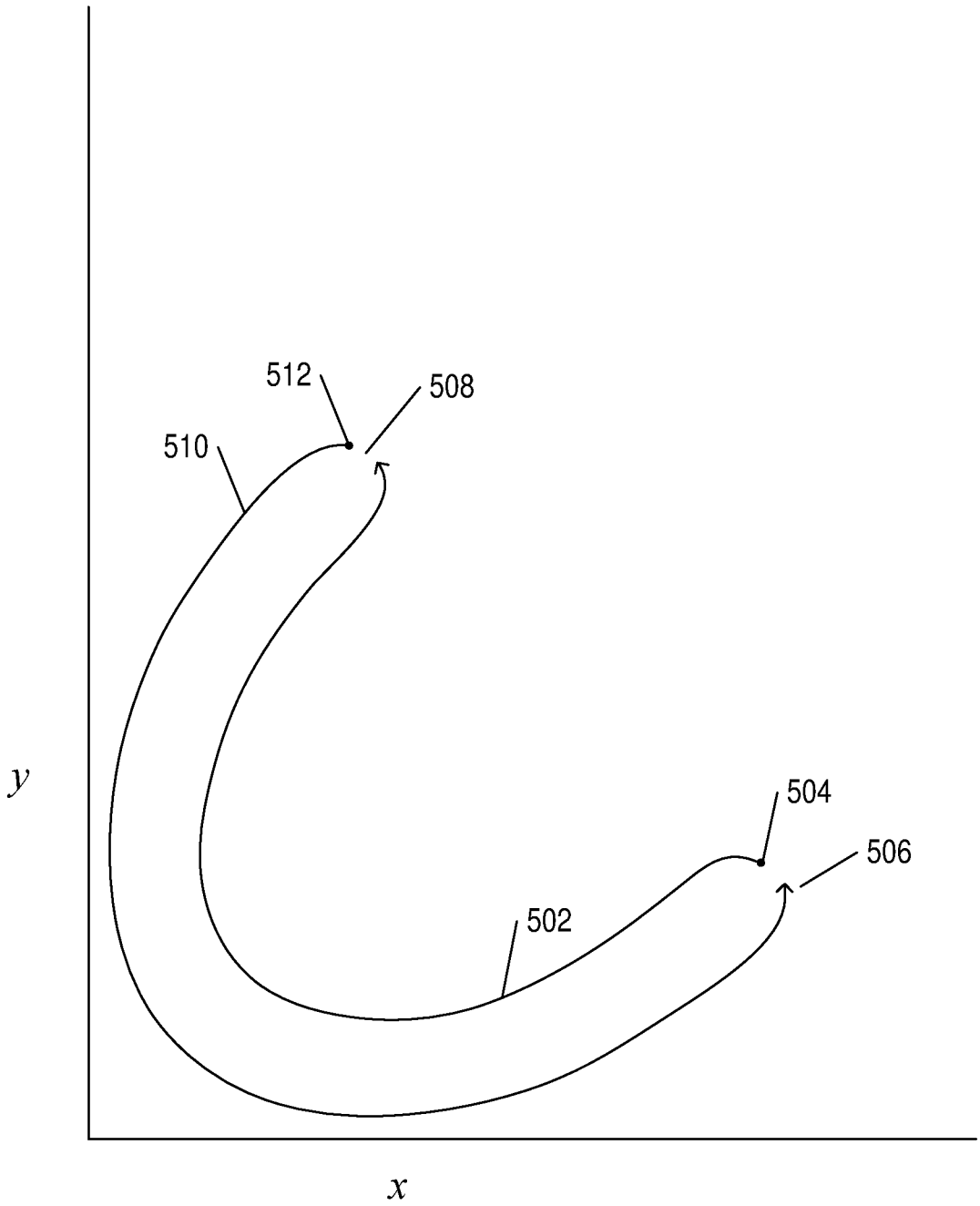

FIG. 5A

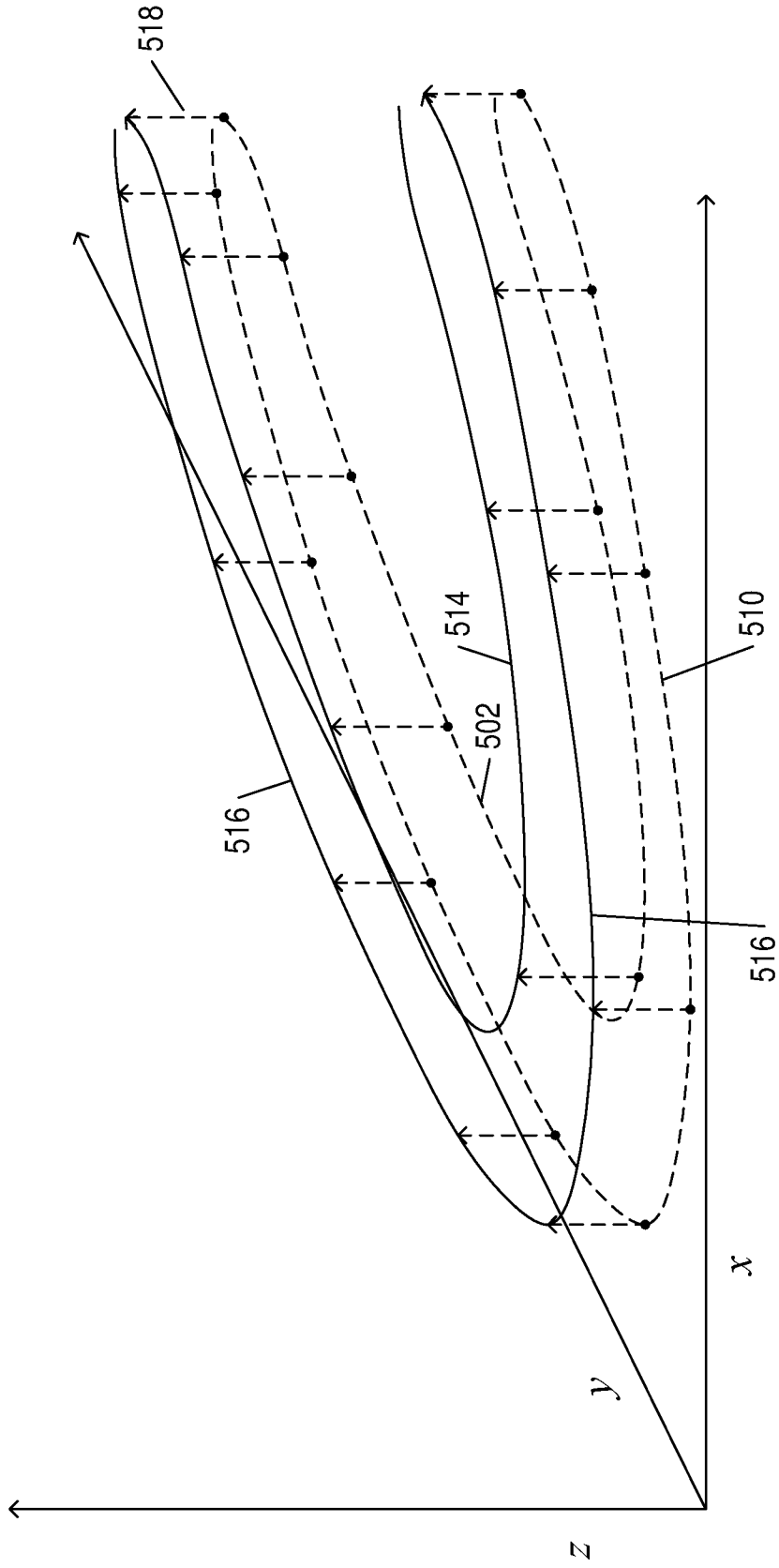

FIG. 5B

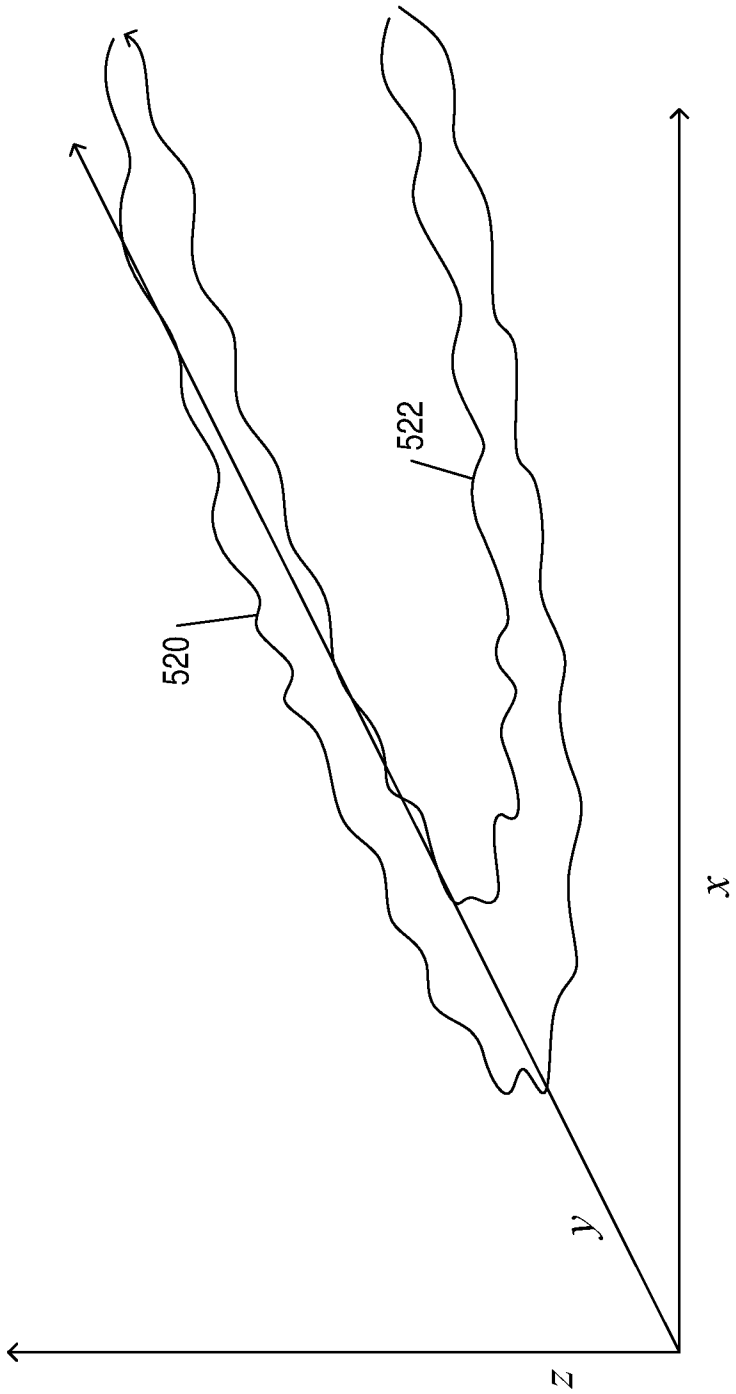

FIG. 5C

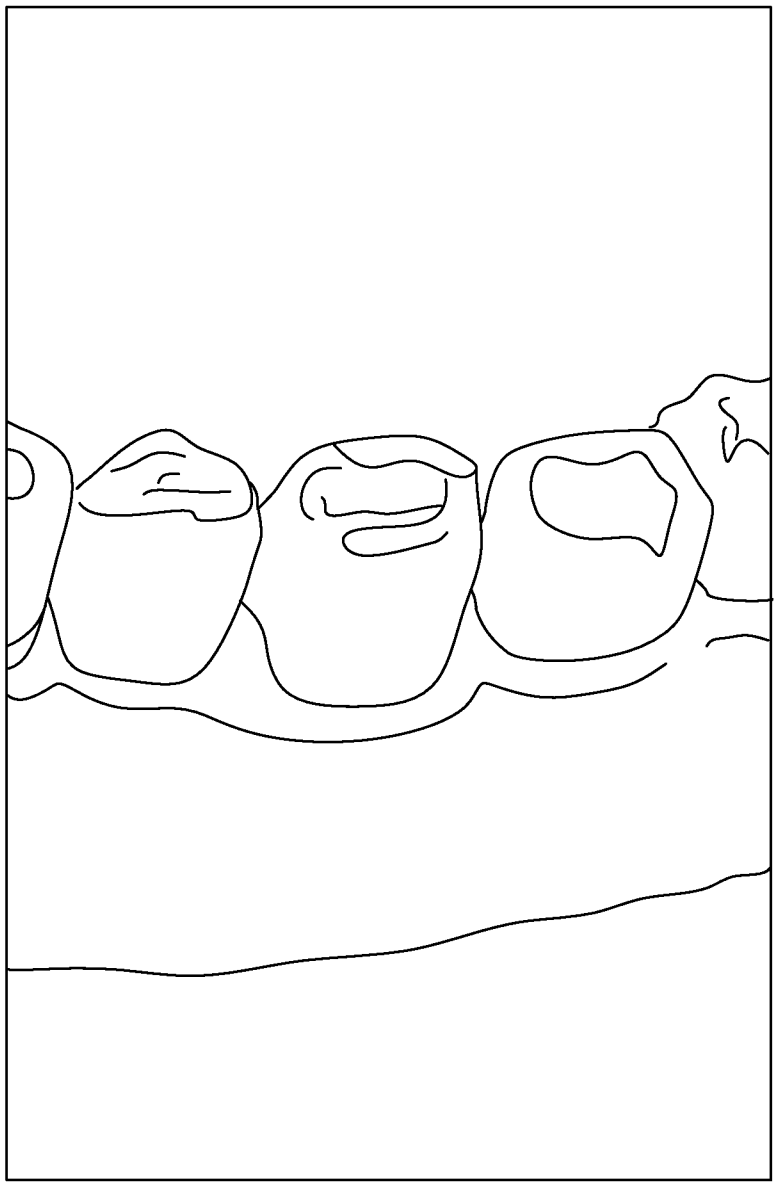

FIG. 5D

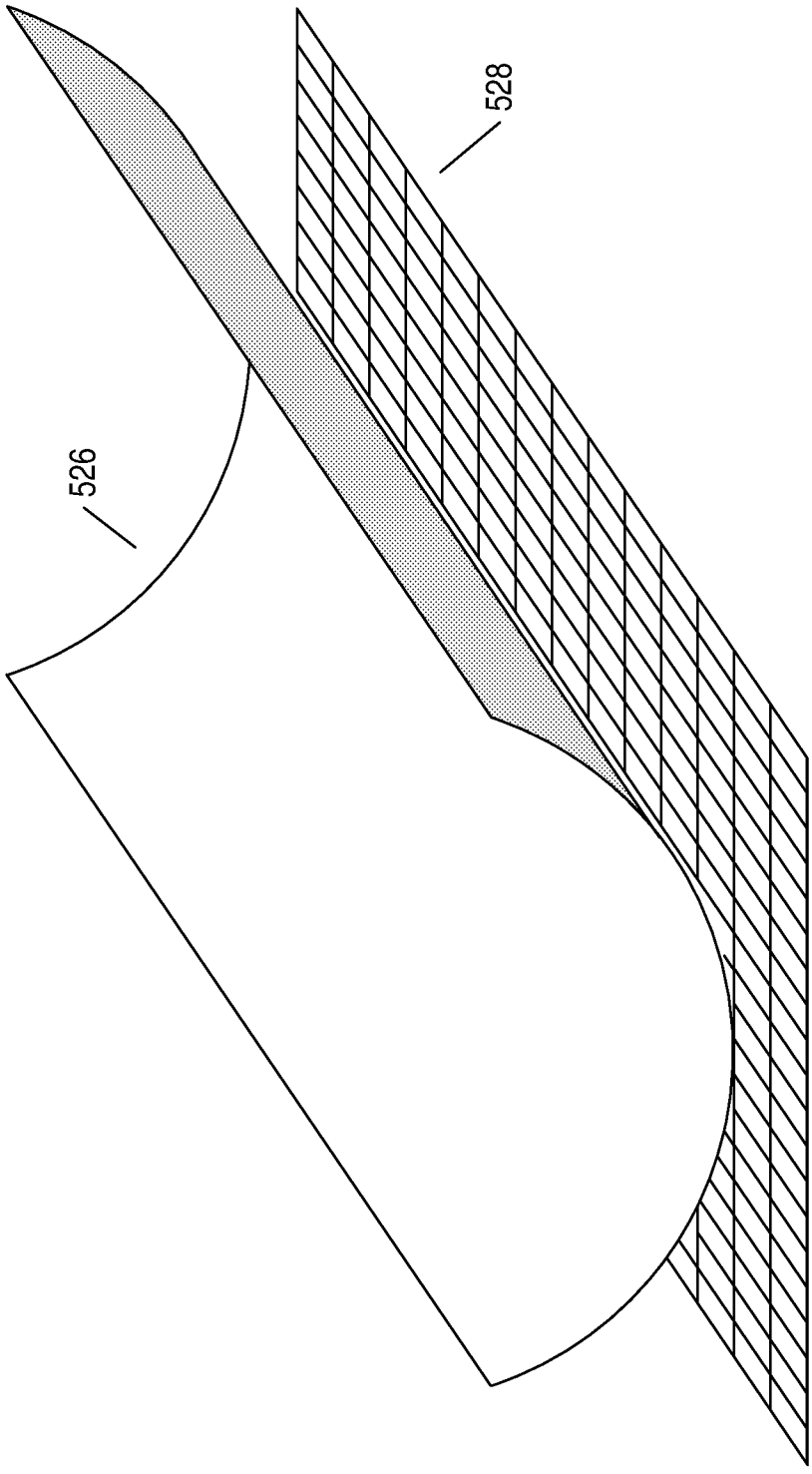

FIG. 5E

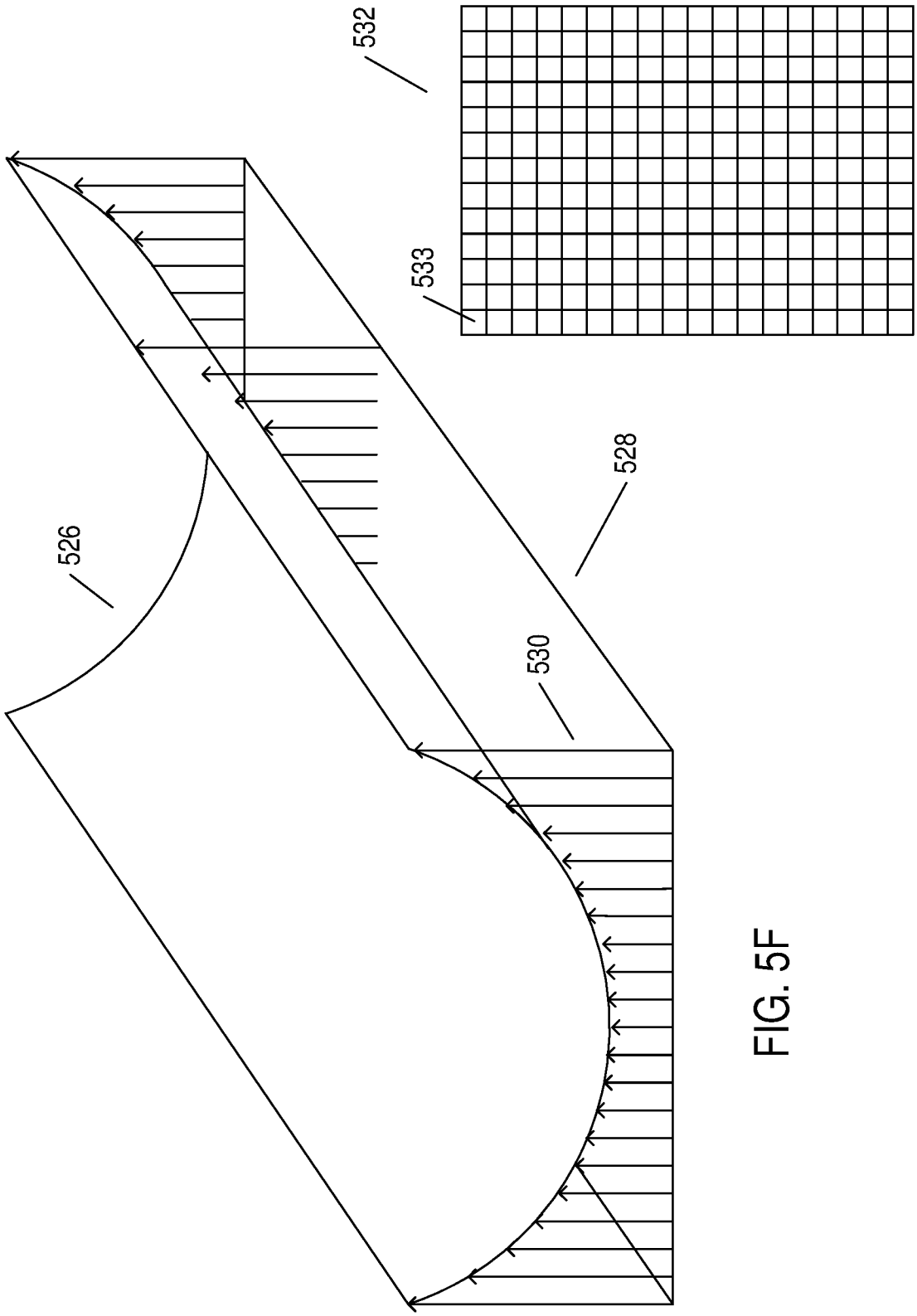

FIG. 5F

FIG. G

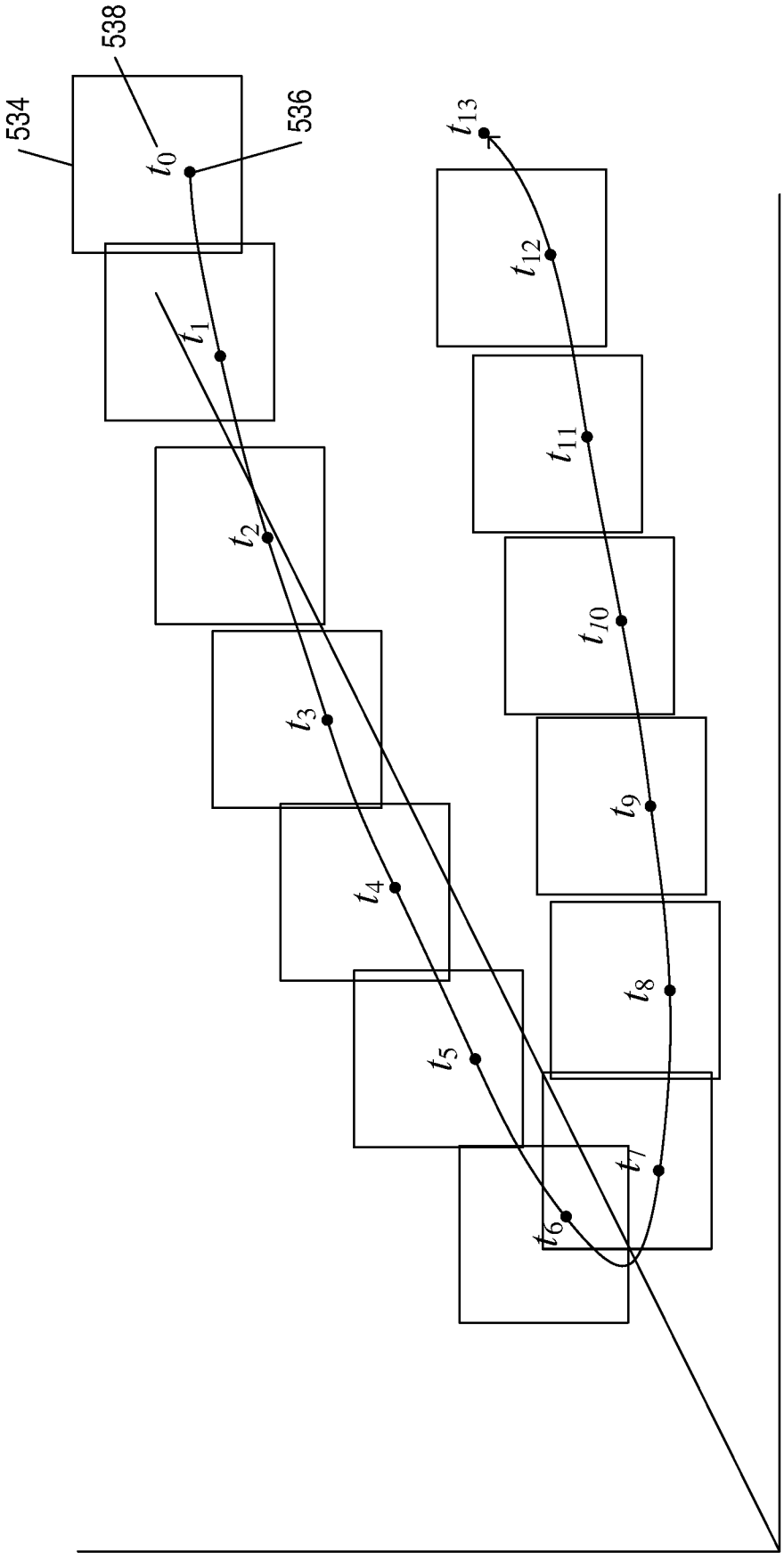

FIG. 5H

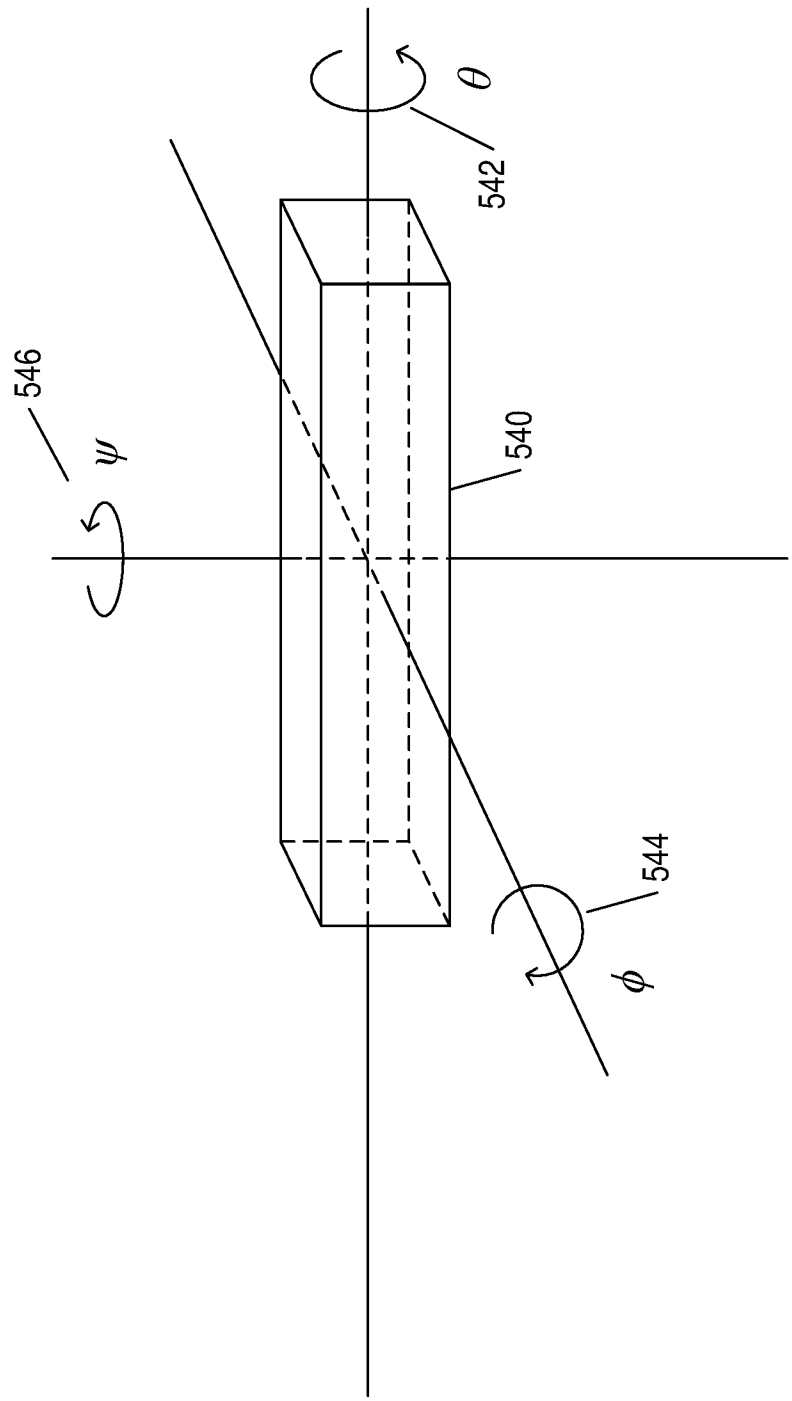

FIG. 5I

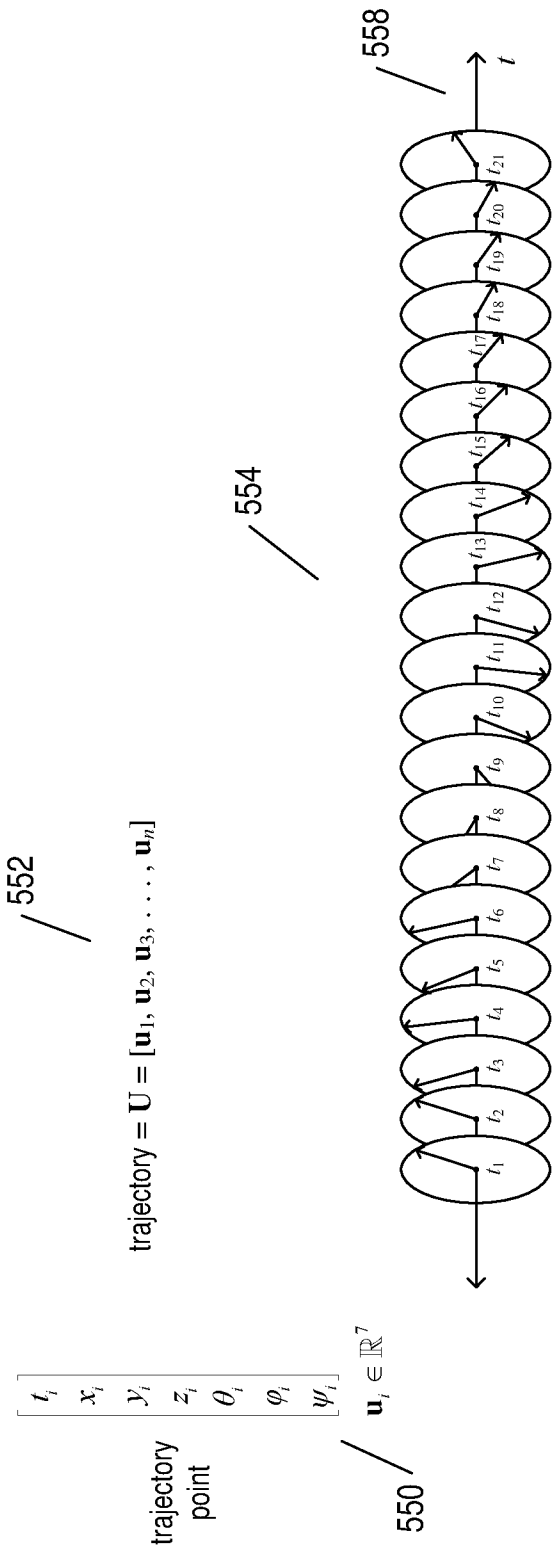
552
trajectory = U = [u1, u2, u3, . . . , un]
554
558
t
t1 t2 t3 t4 t5 t6 t7 t8 t9 t10 t11 t12 t13 t14 t15 t16 t17 t18 t19 t20 t21
trajectory point
ti xi yi zi θi φi ψi
ui ∈ ℝ7
550
xi yi zi θi ϕi ψi
≅
ti
556

FIG. 5J

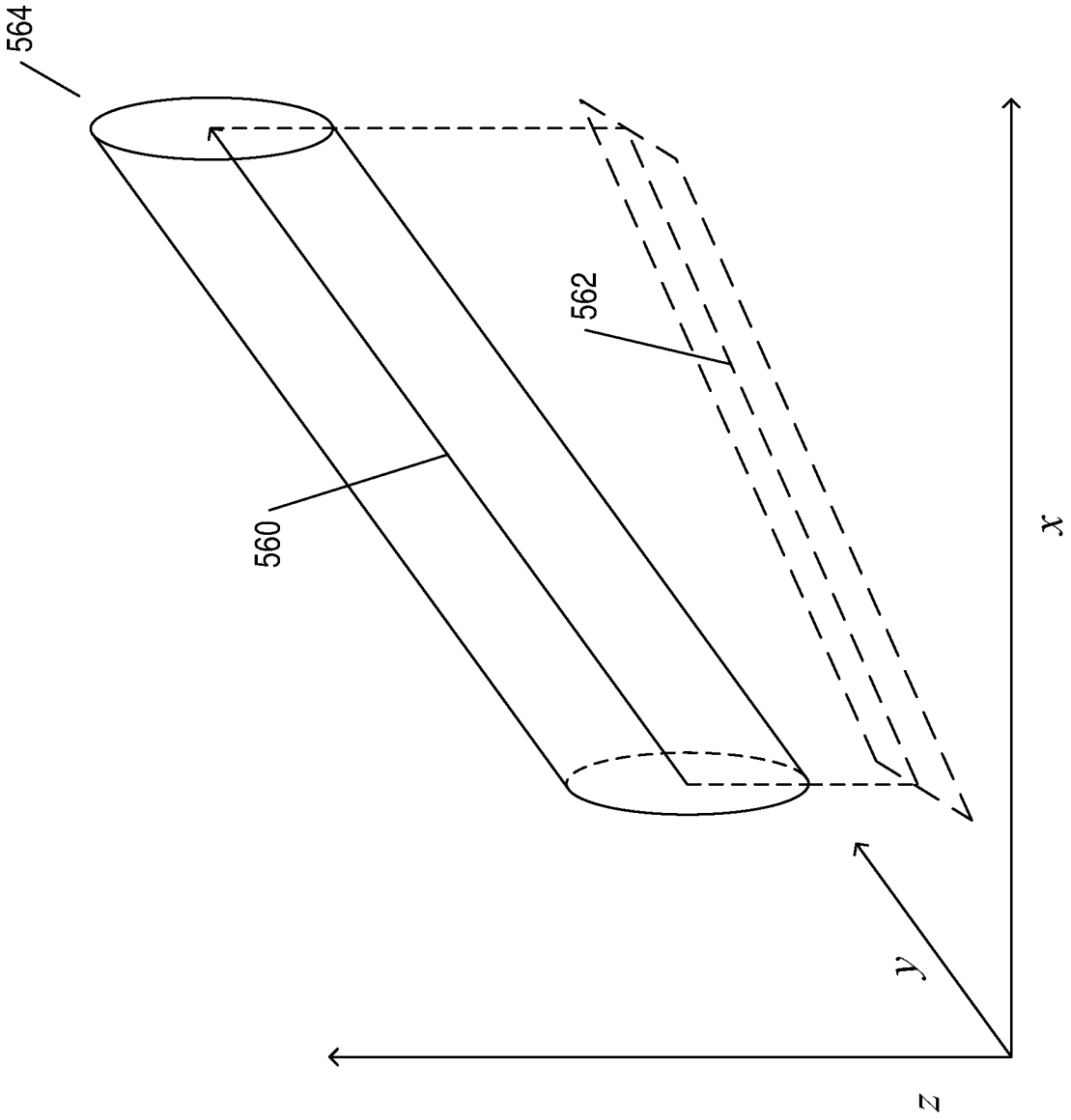

FIG. 5K

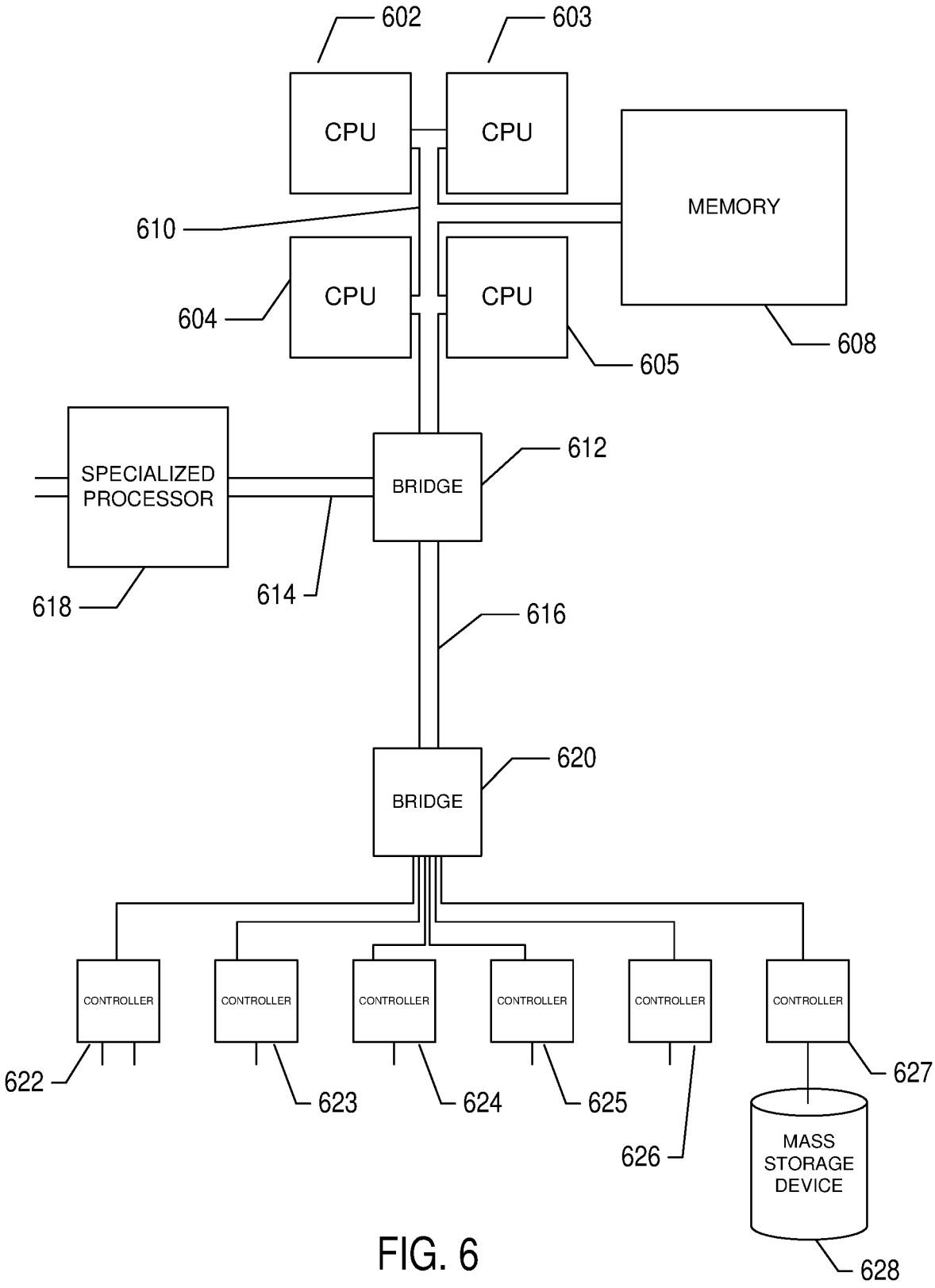
602
603
CPU
CPU
MEMORY
610
CPU
CPU
604
605
608
SPECIALIZED PROCESSOR
BRIDGE
612
618
614
616
BRIDGE
620
CONTROLLER
CONTROLLER
CONTROLLER
CONTROLLER
CONTROLLER
CONTROLLER
622
623
624
625
626
627
MASS STORAGE DEVICE
628

FIG. 6

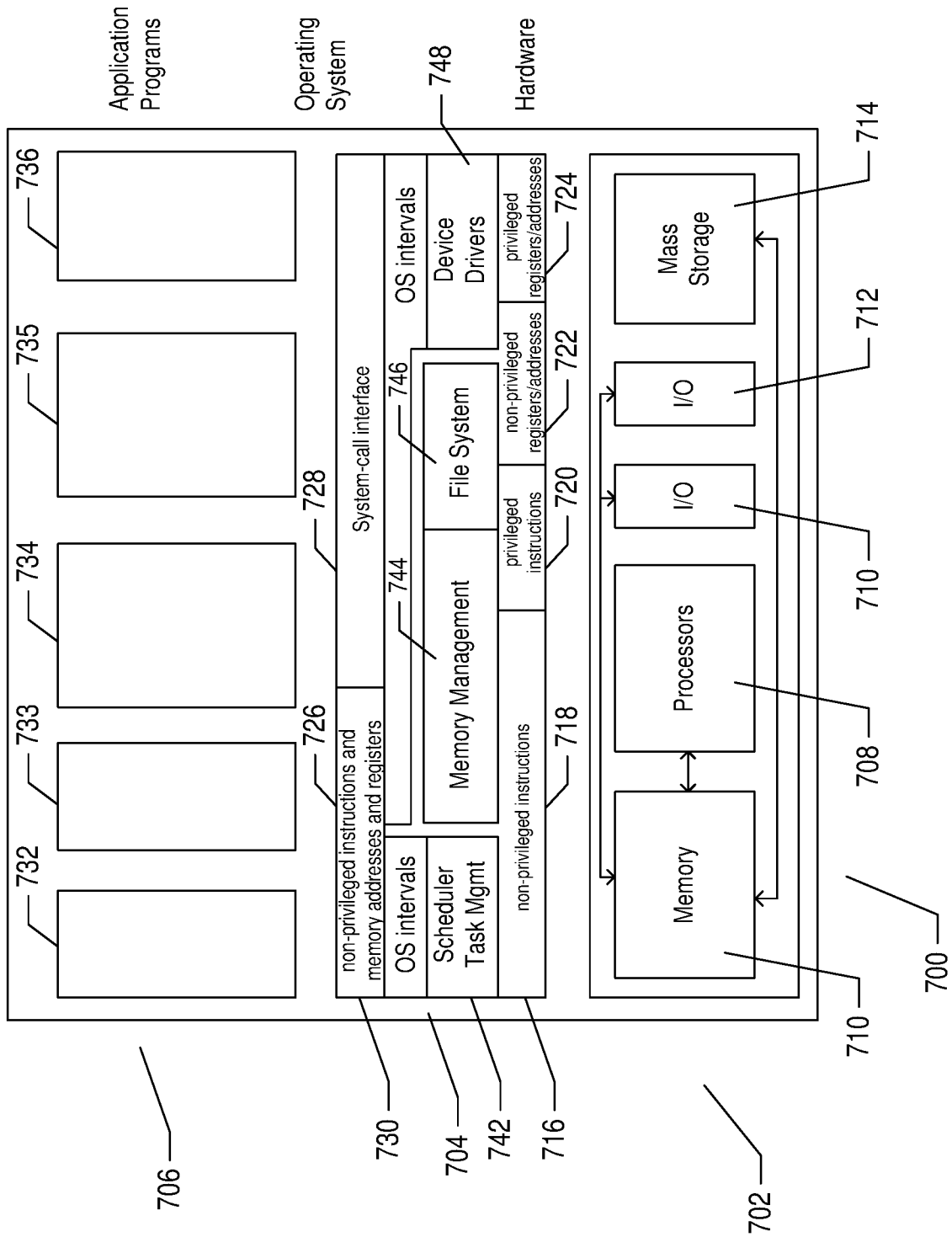
Application Programs
Operating System
Hardware
732
733
734
735
736
728
726
System-call interface
non-privileged instructions and memory addresses and registers
OS intervals
Scheduler Task Mgmt
744
Memory Management
746
File System
OS intervals
Device Drivers
748
non-privileged instructions
718
privileged instructions
720
non-privileged registers/addresses
722
privileged registers/addresses
724
Memory
Processors
I/O
I/O
Mass Storage
714
712
710
708
710
700
706
730
704
742
716
702

FIG. 7A

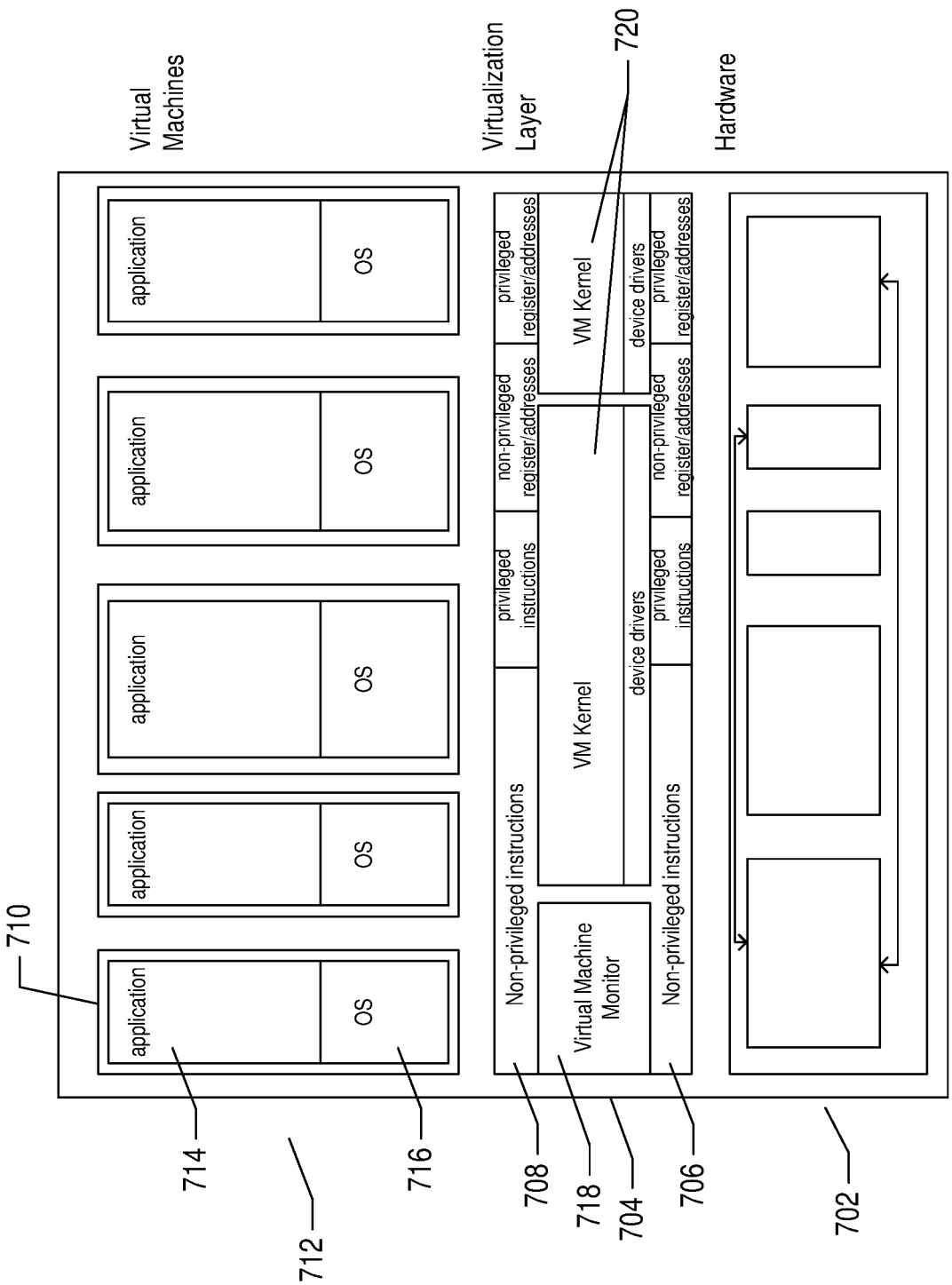
Virtual Machines
Virtualization Layer
Hardware
720
application
OS
privileged register/addresses
non-privileged register/addresses
VM Kernel
device drivers
privileged instructions
Non-privileged instructions
Virtual Machine Monitor
710
714
712
716
708
718
704
706
702
700

FIG. 7B

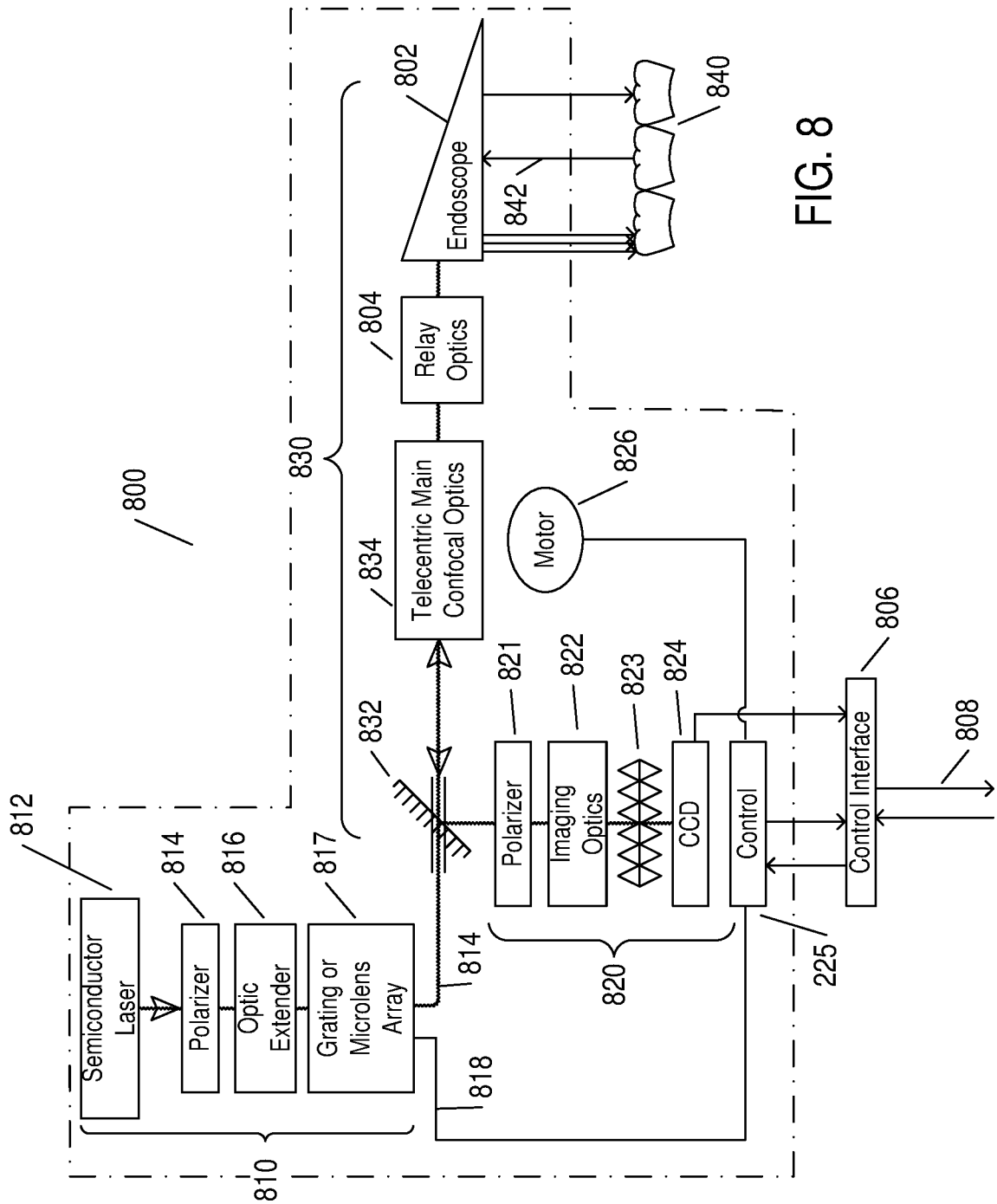
800
810
812
Semiconductor Laser
814
Polarizer
816
Optic Extender
817
Grating or Microlens Array
818
820
821
Polarizer
822
Imaging Optics
823
824
CCD
825
Control
826
Motor
830
832
834
Telecentric Main Confocal Optics
804
Relay Optics
802
Endoscope
840
842
806
Control Interface
808

FIG. 8

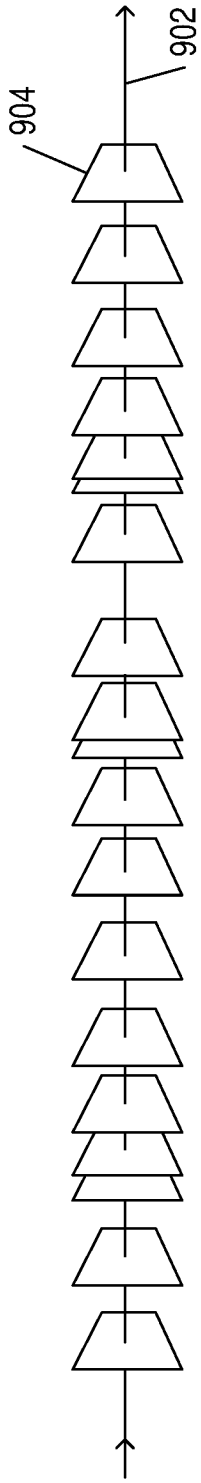

FIG. 9

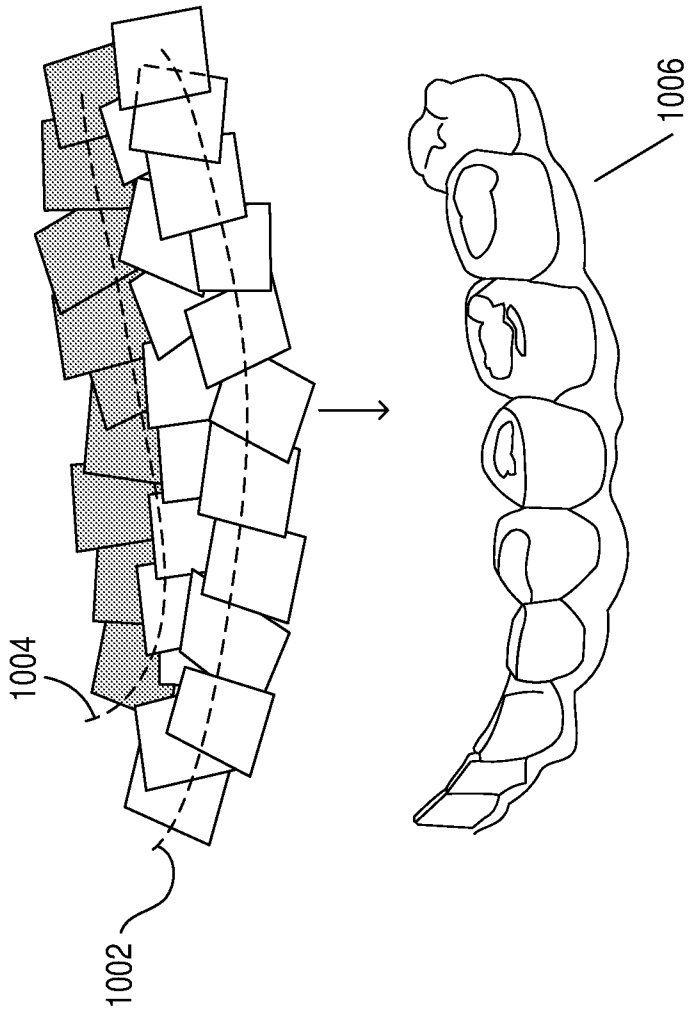

FIG. 10

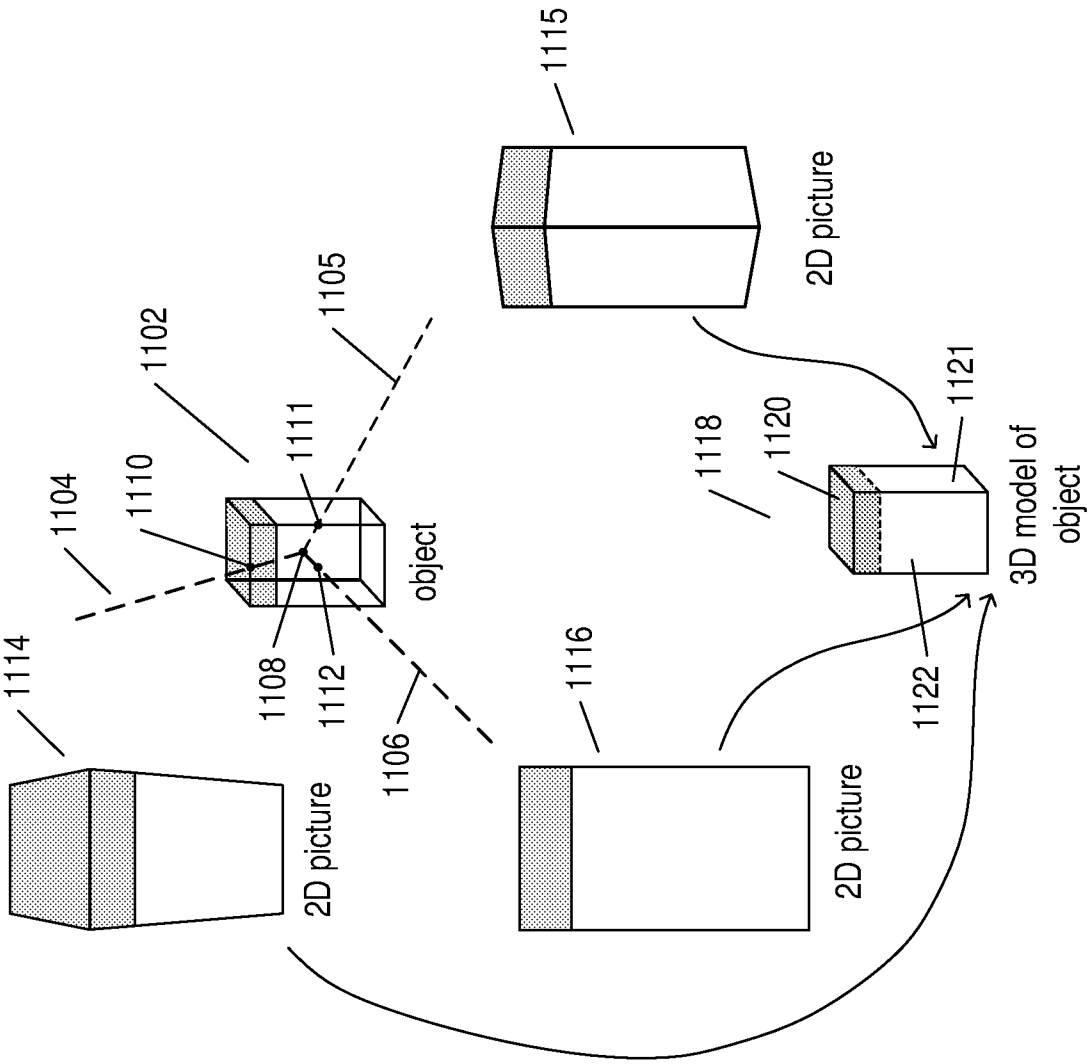
1115
2D picture
1102
1105
1111
1110
1104
object
1121
1118
1120
3D model of object
1114
1108
1112
1106
1116
1122
2D picture
2D picture

FIG. 11A

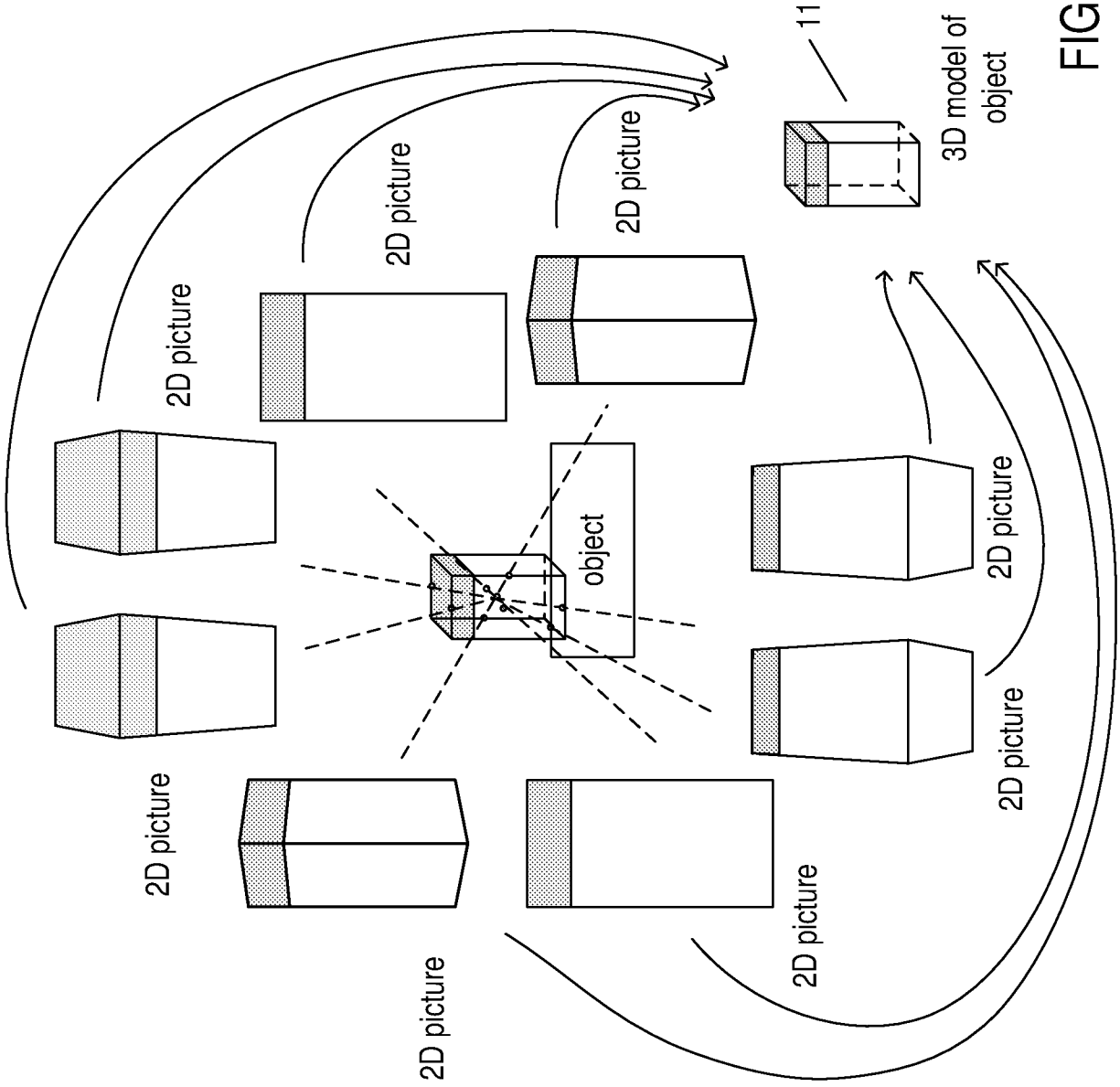
1124
3D model of object
2D picture
2D picture
2D picture
2D picture
2D picture
2D picture
2D picture
2D picture
object

FIG. 11B

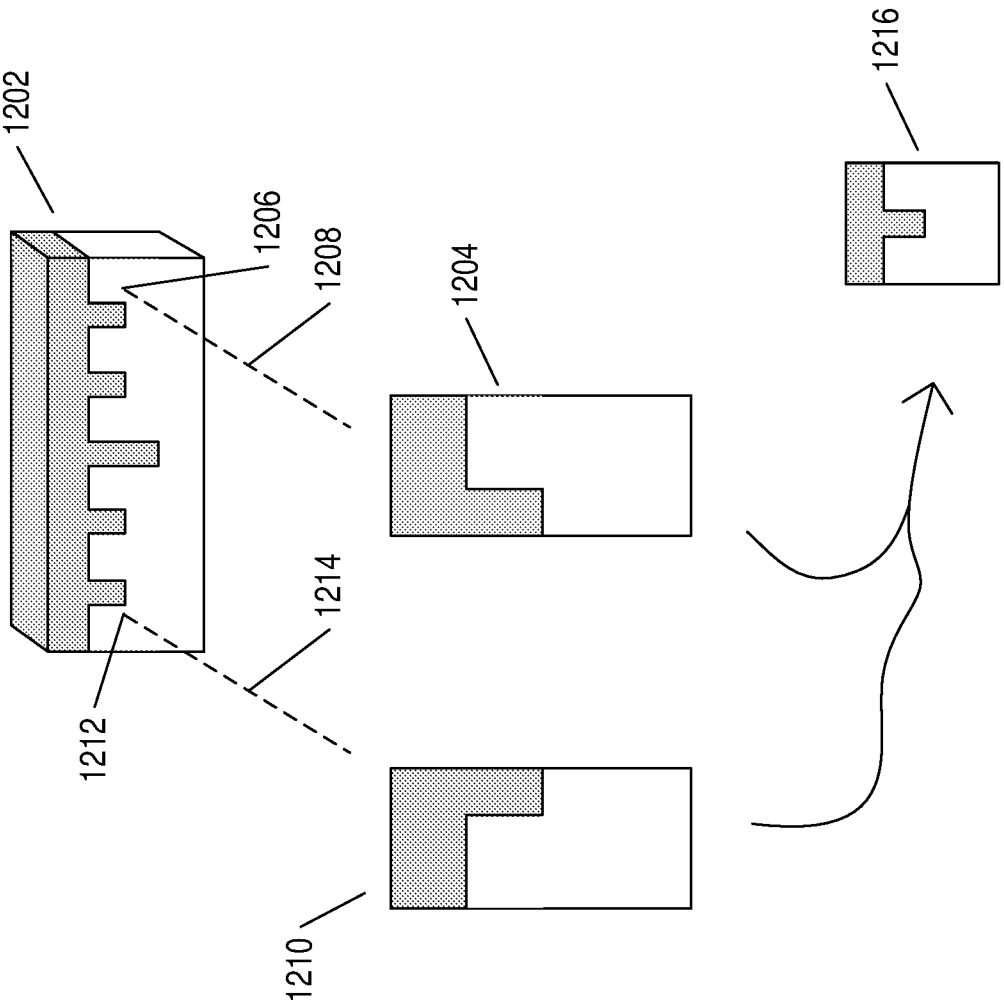

FIG. 12A

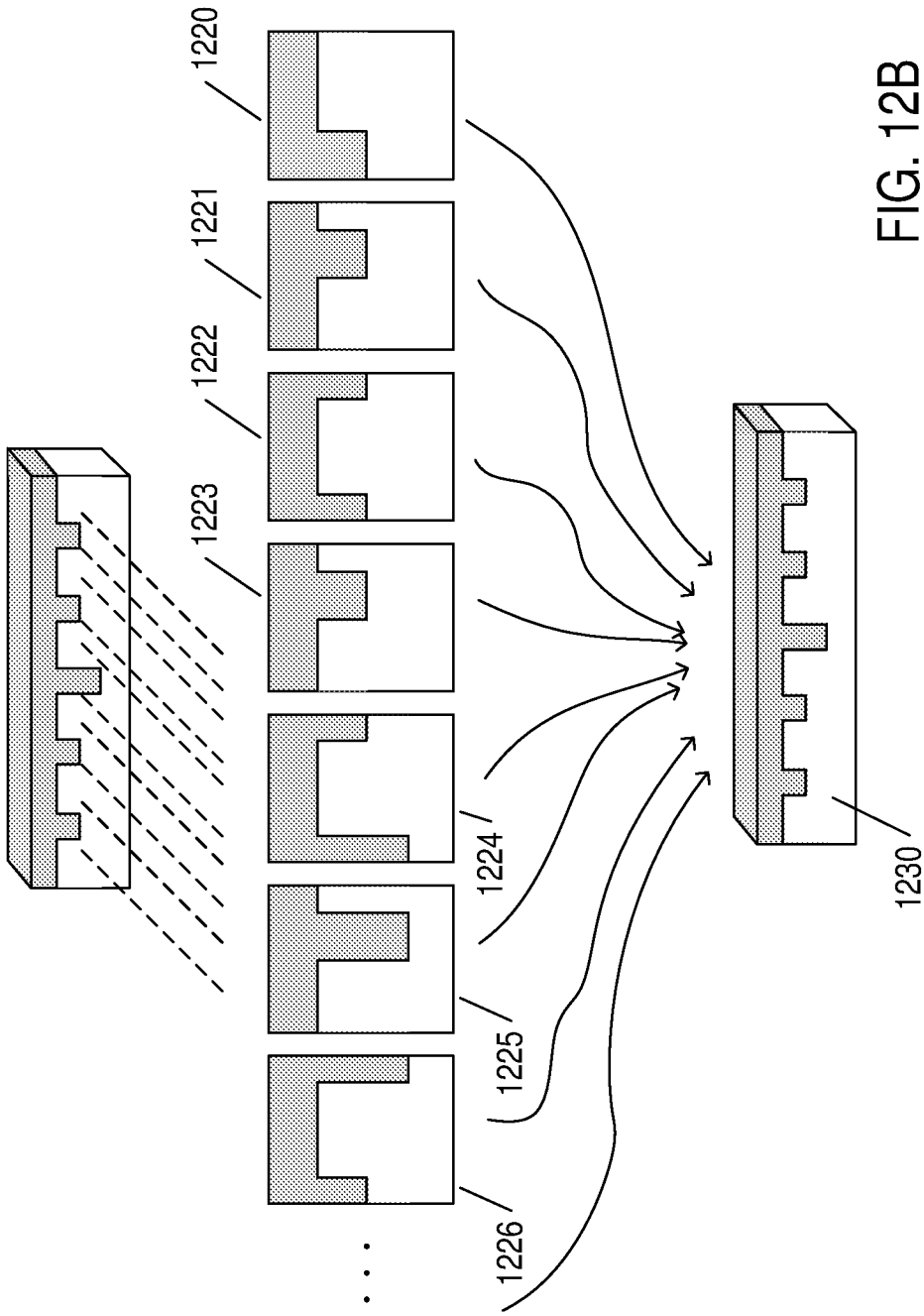

FIG. 12B

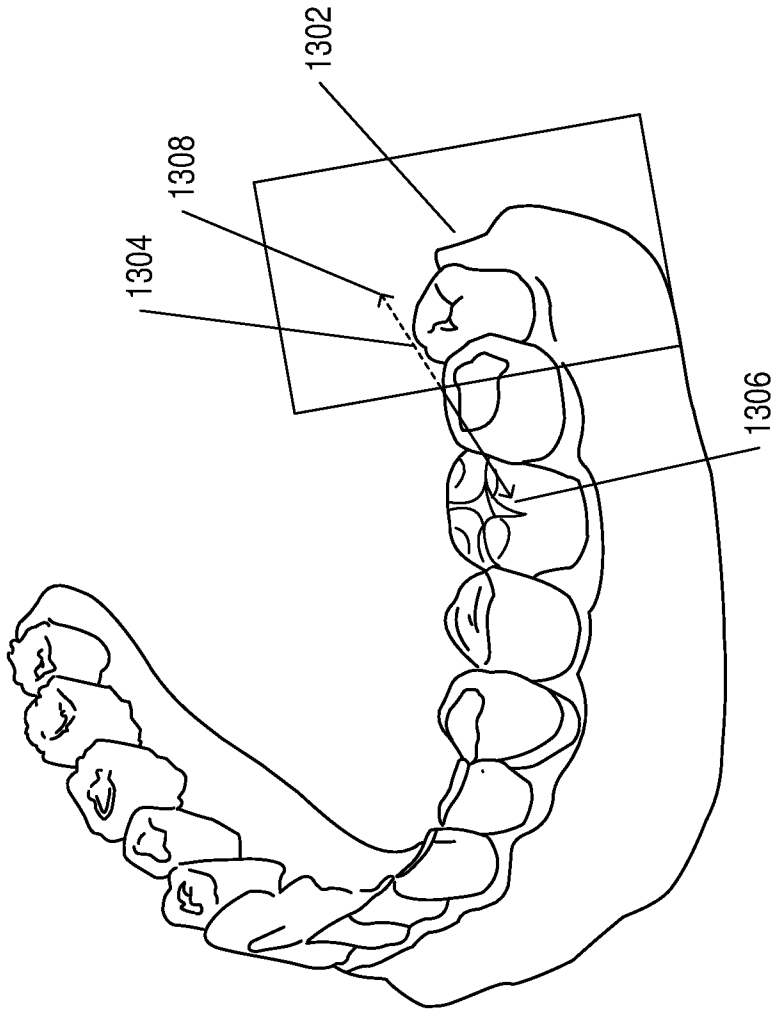

FIG. 13

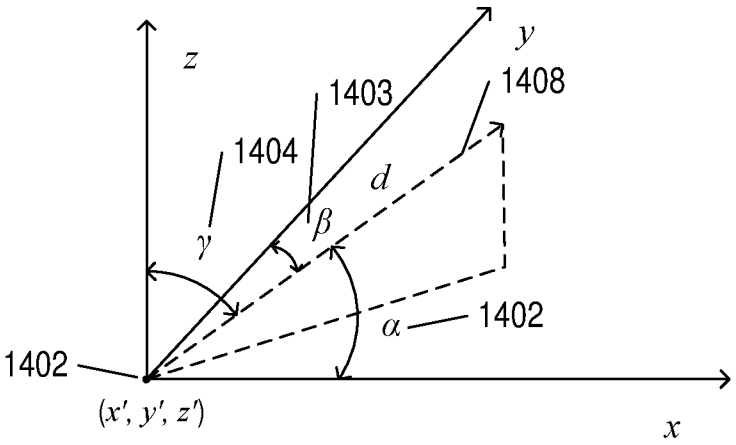

FIG. 14A

$$\begin{bmatrix} t_i \\ x_i \\ y_i \\ z_i \\ \theta_i \\ \varphi_i \\ \psi_i \end{bmatrix} = \mathbf{u}_i = f\left(t, d, x', y', z', \alpha, \beta, \gamma\right)$$

1408

FIG. 14B

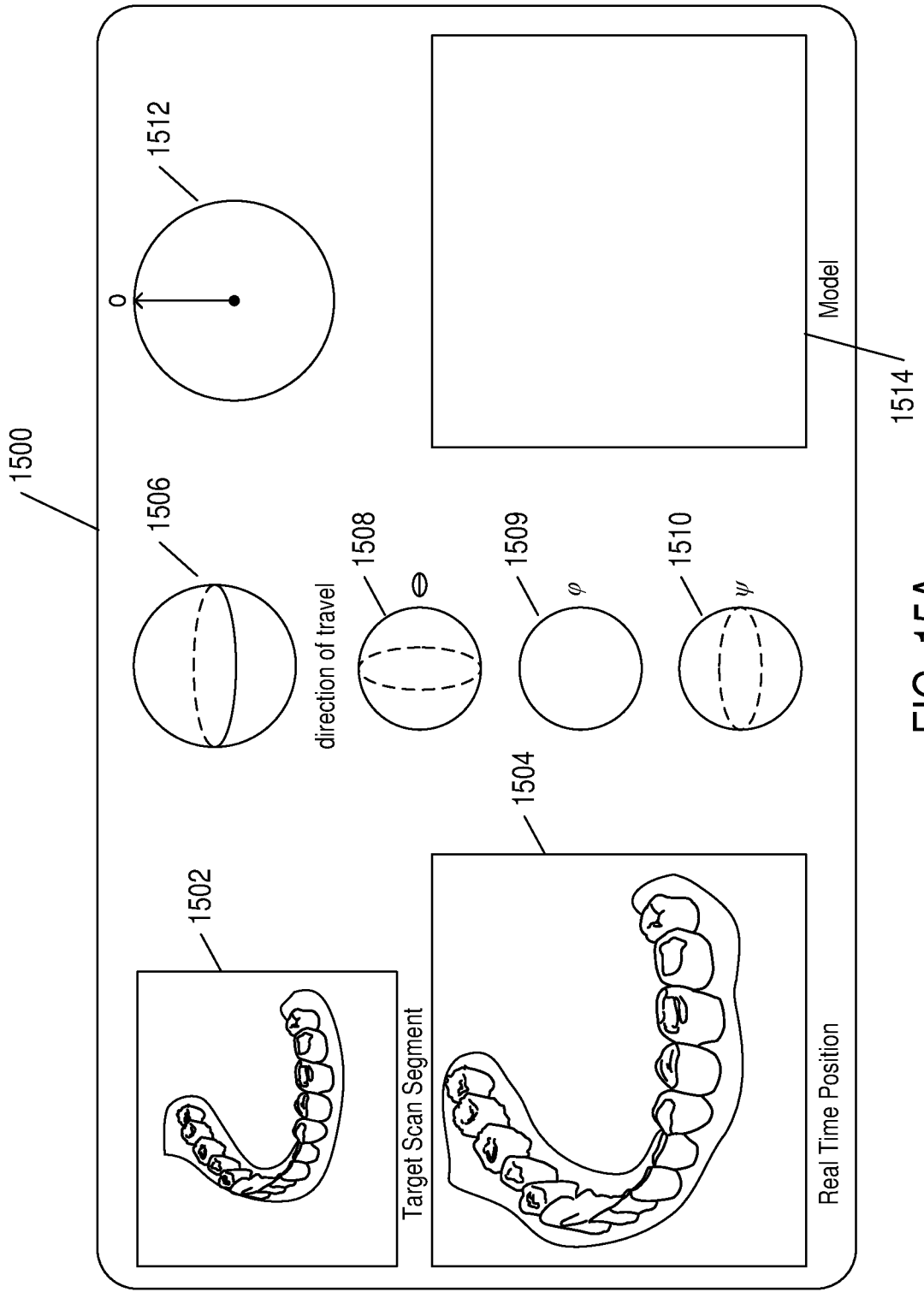
1500
1502
Target Scan Segment
1504
Real Time Position
1506
direction of travel
1508
1509
1510
1512
0
Model
1514

FIG. 15A

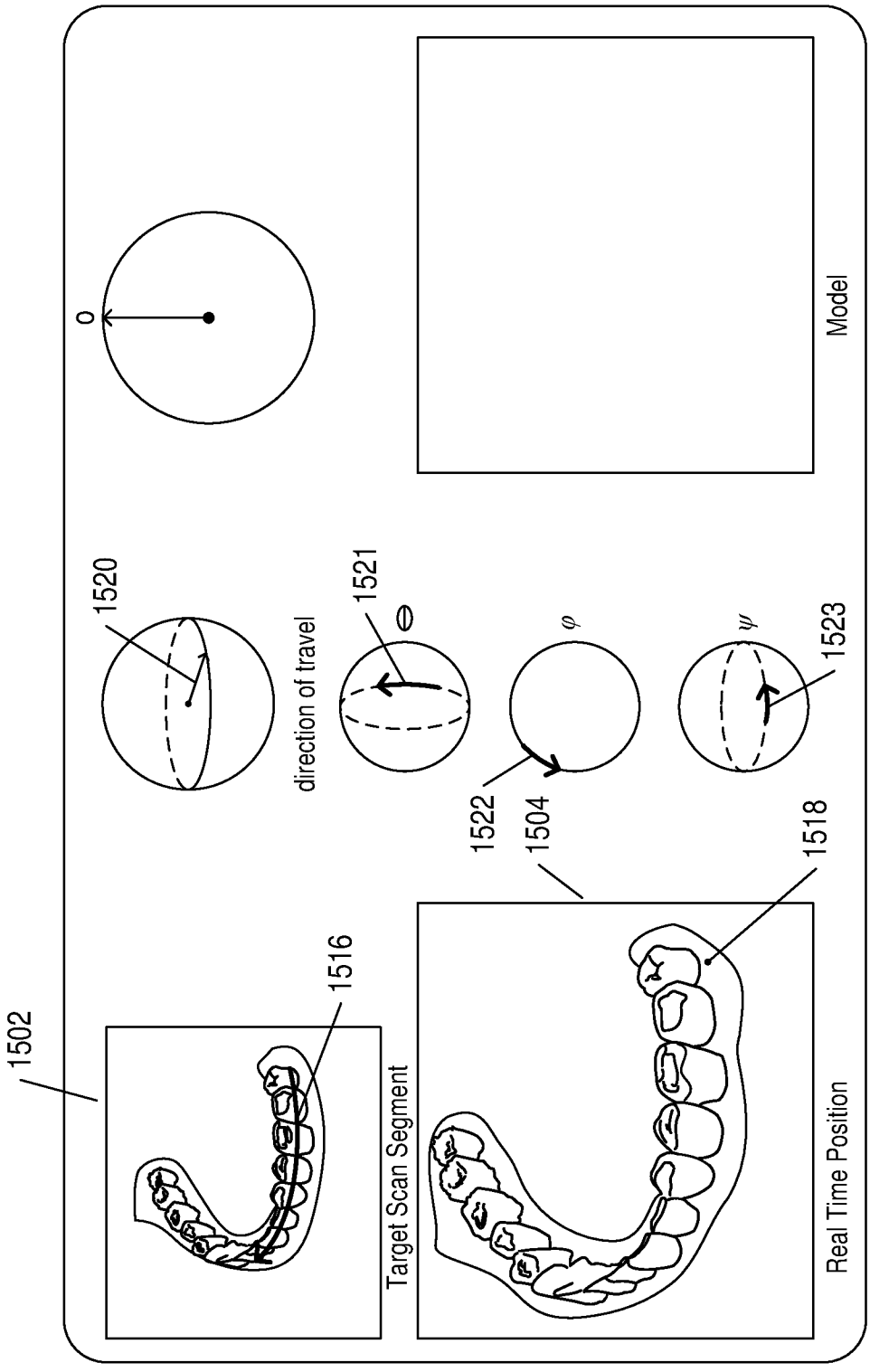
1502
1516
Target Scan Segment
1504
1518
Real Time Position
1520
direction of travel
1521
1522
1523
0
Model

FIG. 15B

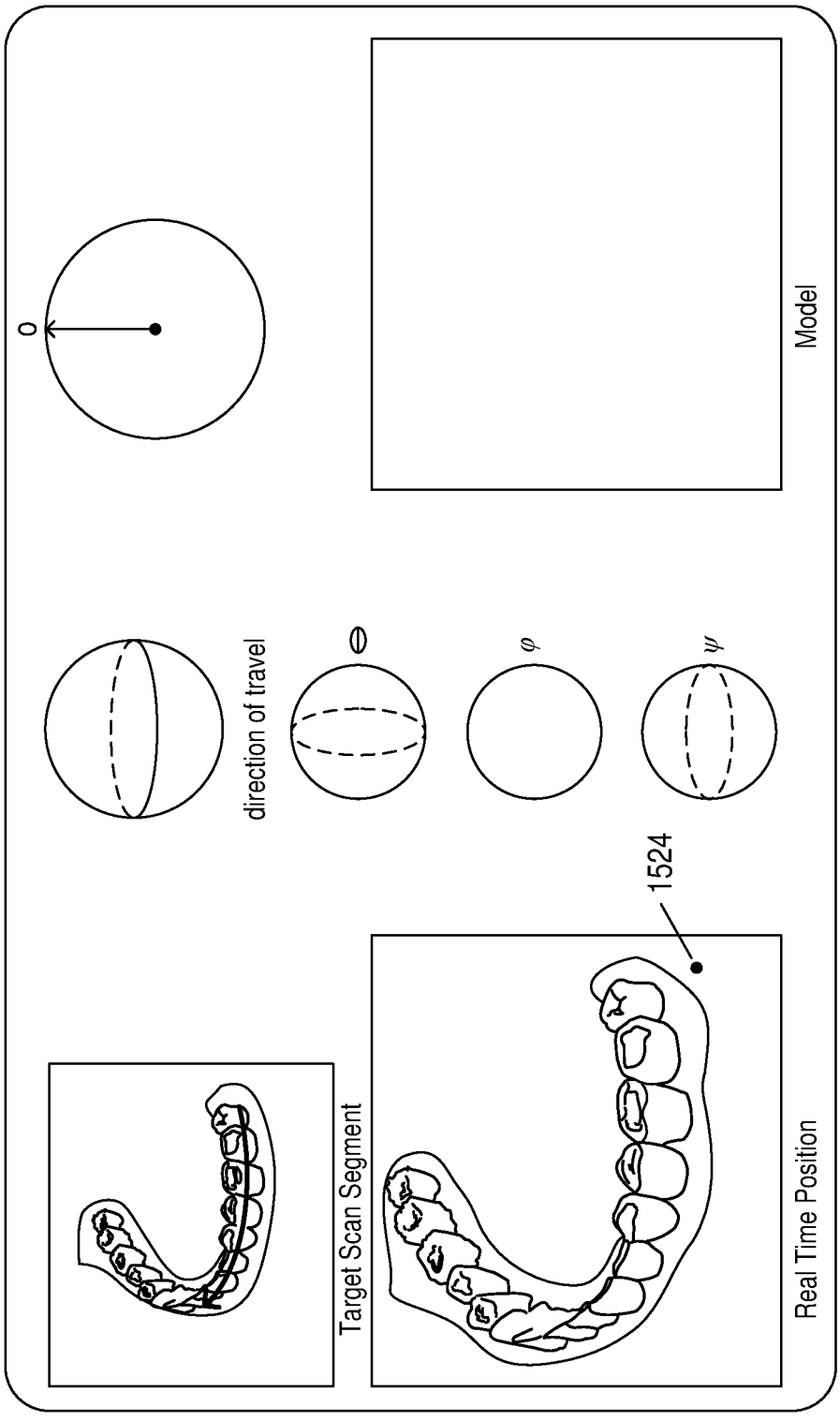
0
direction of travel
θ
φ
ψ
Model
1524
Target Scan Segment
Real Time Position

FIG. 15C

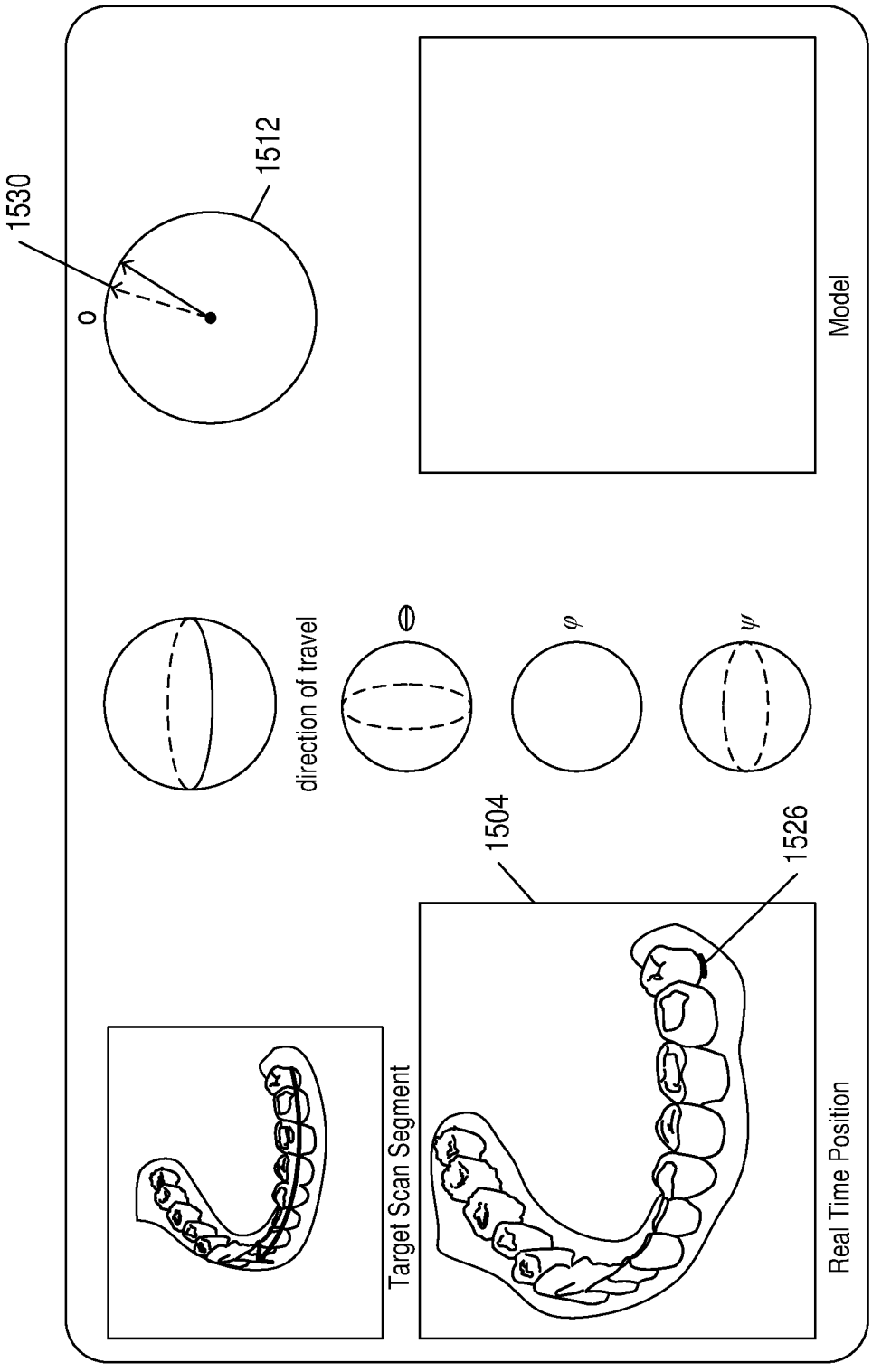
1530
1512
0
Model
direction of travel
θ
φ
ψ
1504
1526
Target Scan Segment
Real Time Position

FIG. 15D

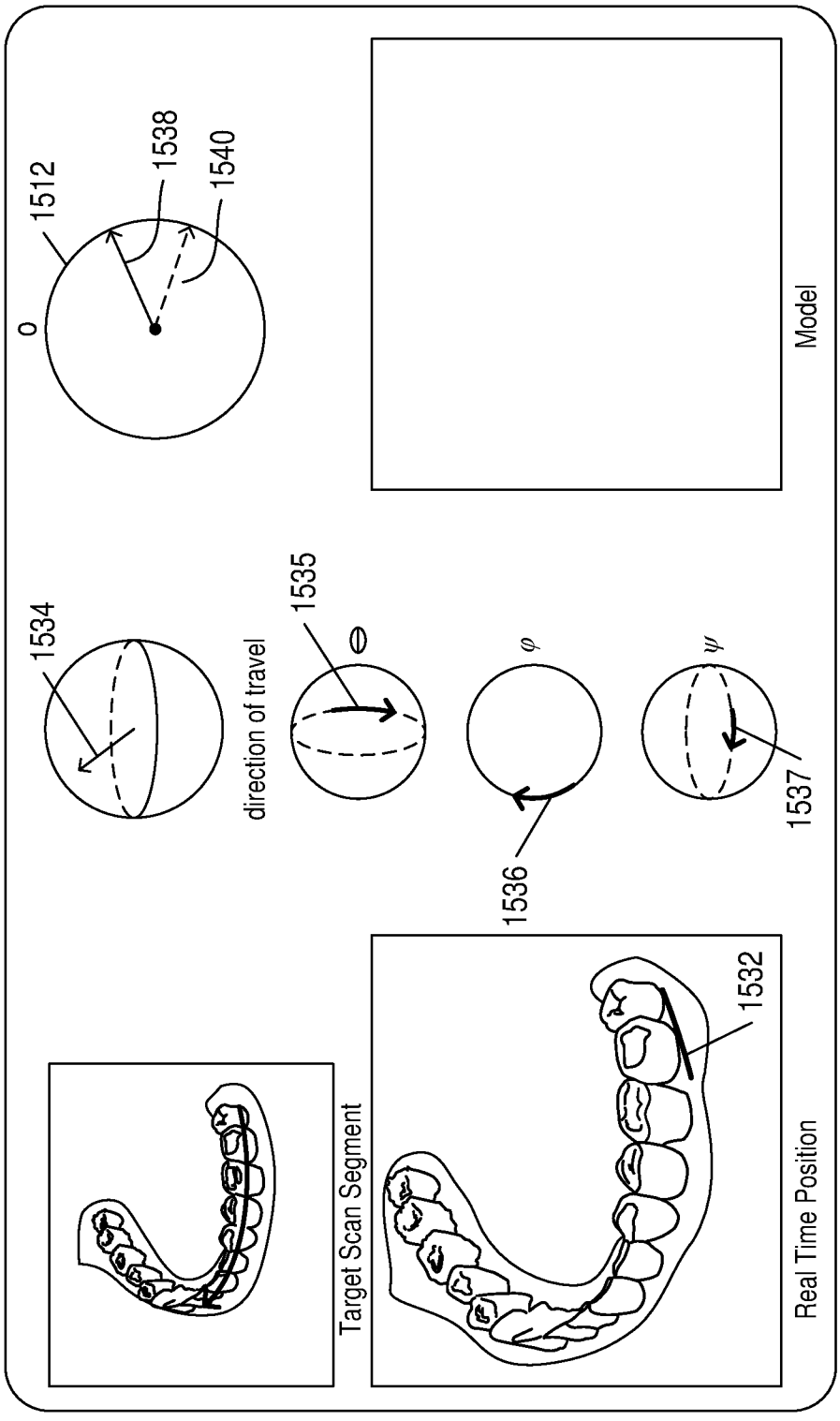
0
1512
1538
1540
1534
direction of travel
1535
θ
φ
ψ
1536
1537
Model
Target Scan Segment
1532
Real Time Position

FIG. 15E

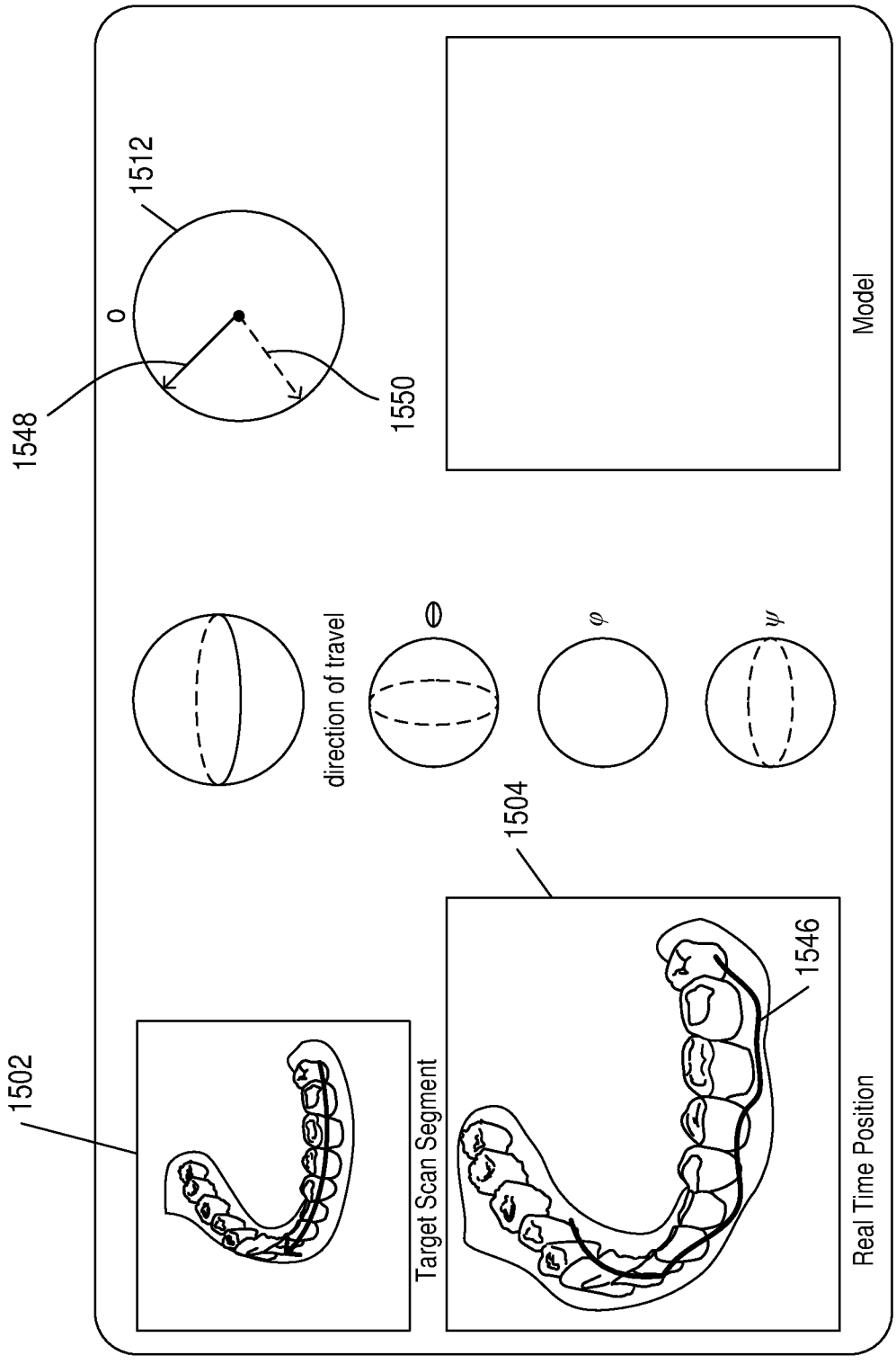
1502
Target Scan Segment
1504
1546
Real Time Position
direction of travel
θ
φ
ψ
1548
0
1512
1550
Model

FIG. 15F

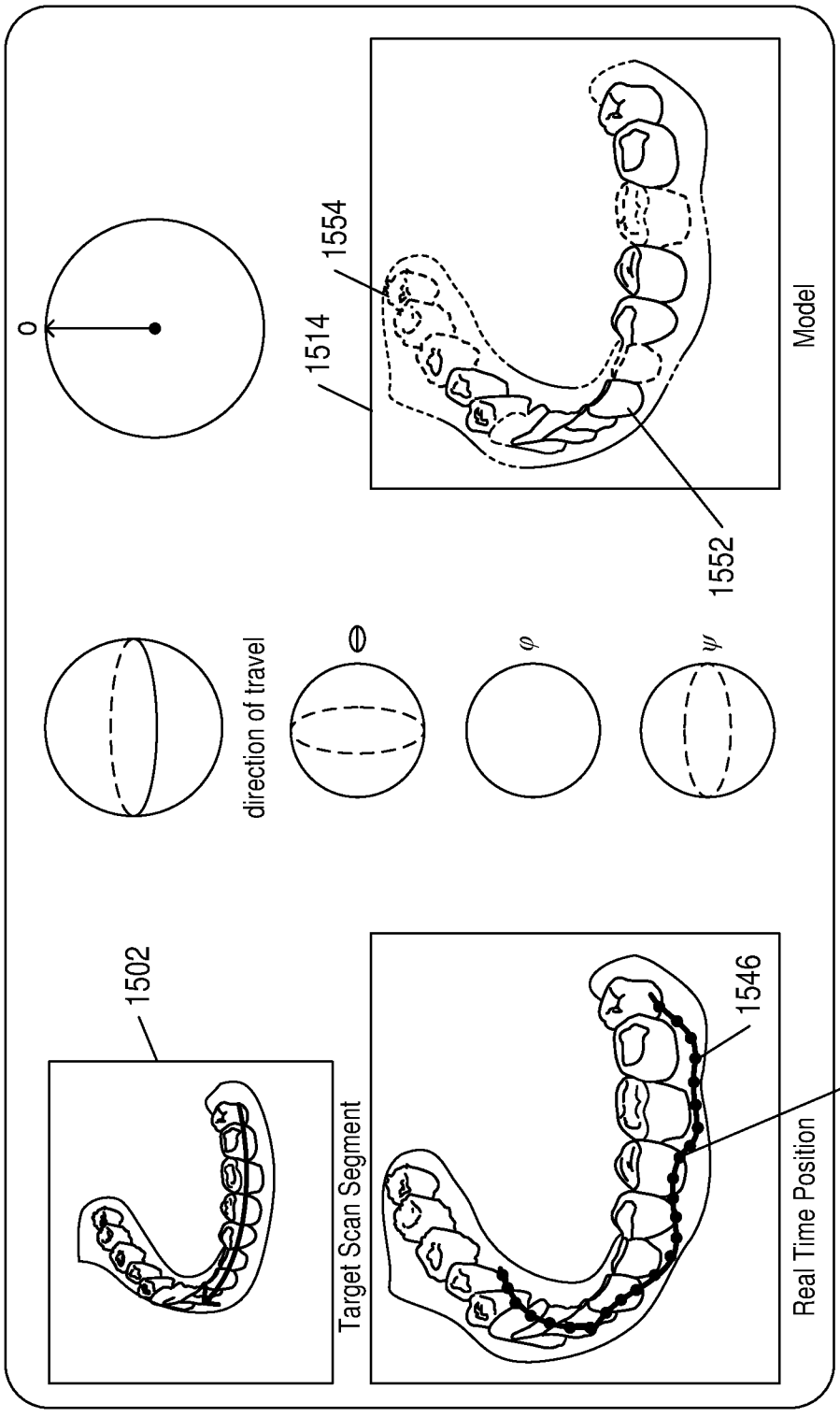
0
1514
1554
Model
1552
direction of travel
θ
φ
ψ
1502
Target Scan Segment
1546
Real Time Position
1556

FIG. 15G

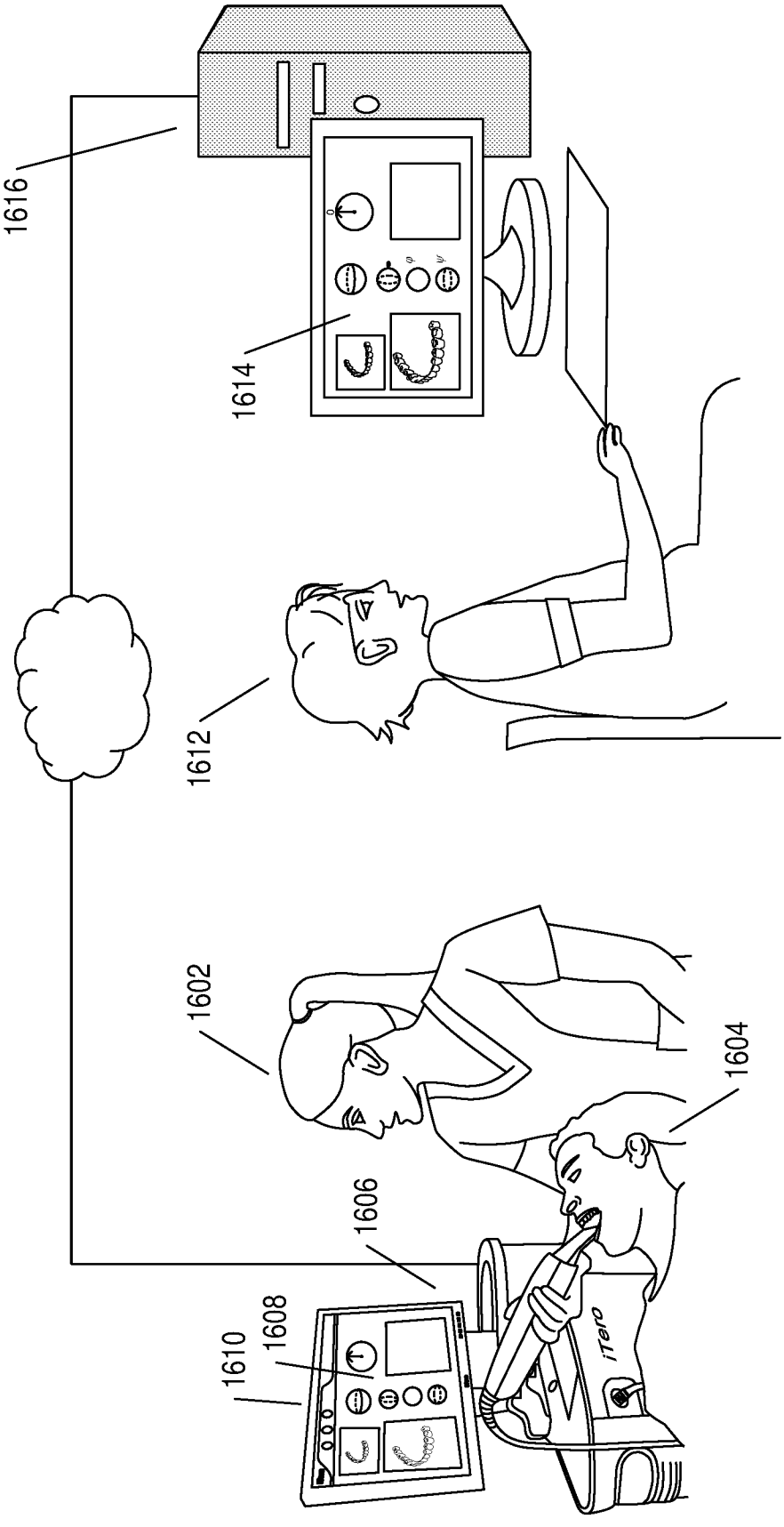

FIG. 16

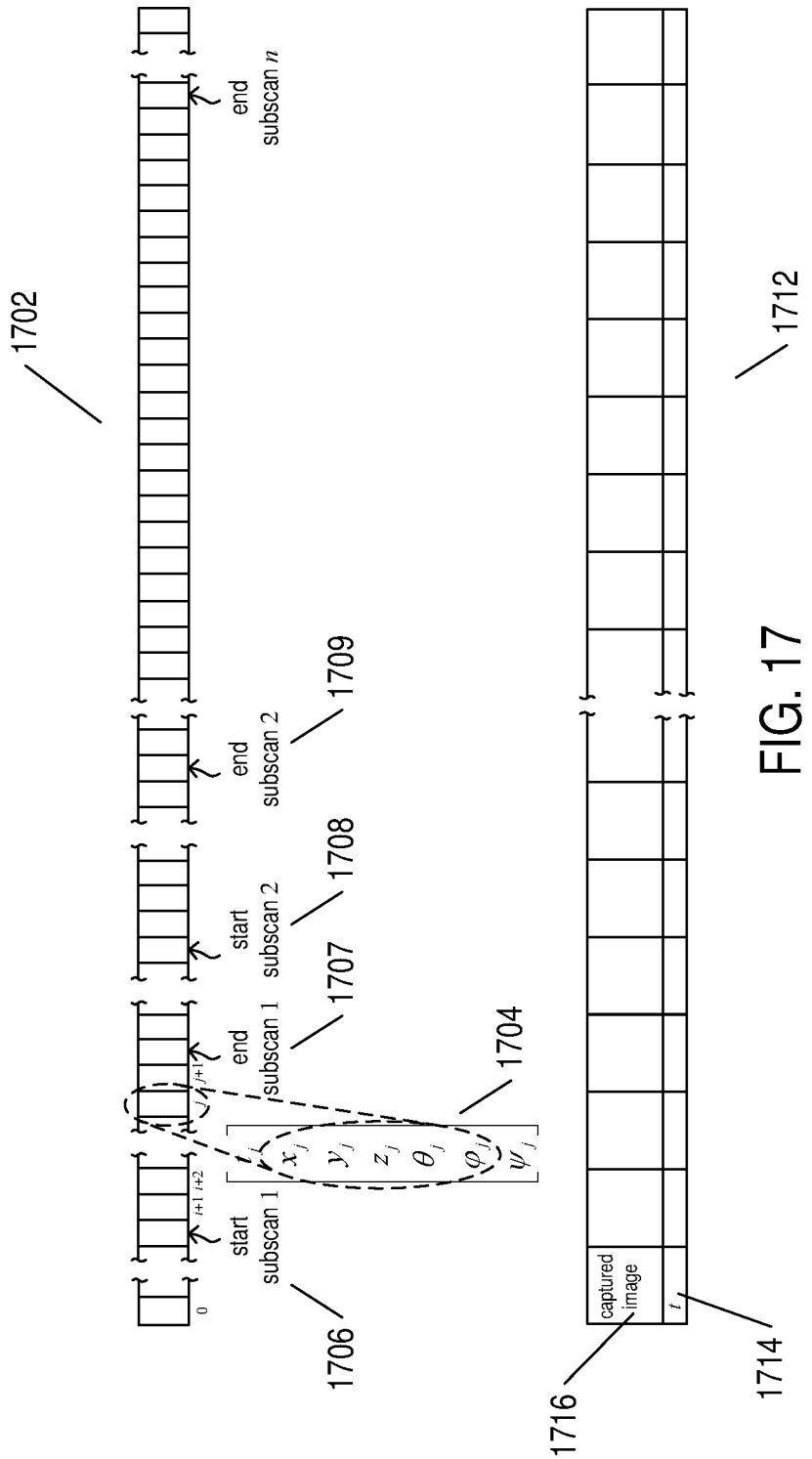
1702
start subscan 1
end subscan 1
start subscan 2
end subscan 2
end subscan n
1706
1707
1708
1709
1704
1712
1714
1716
captured image

FIG. 17

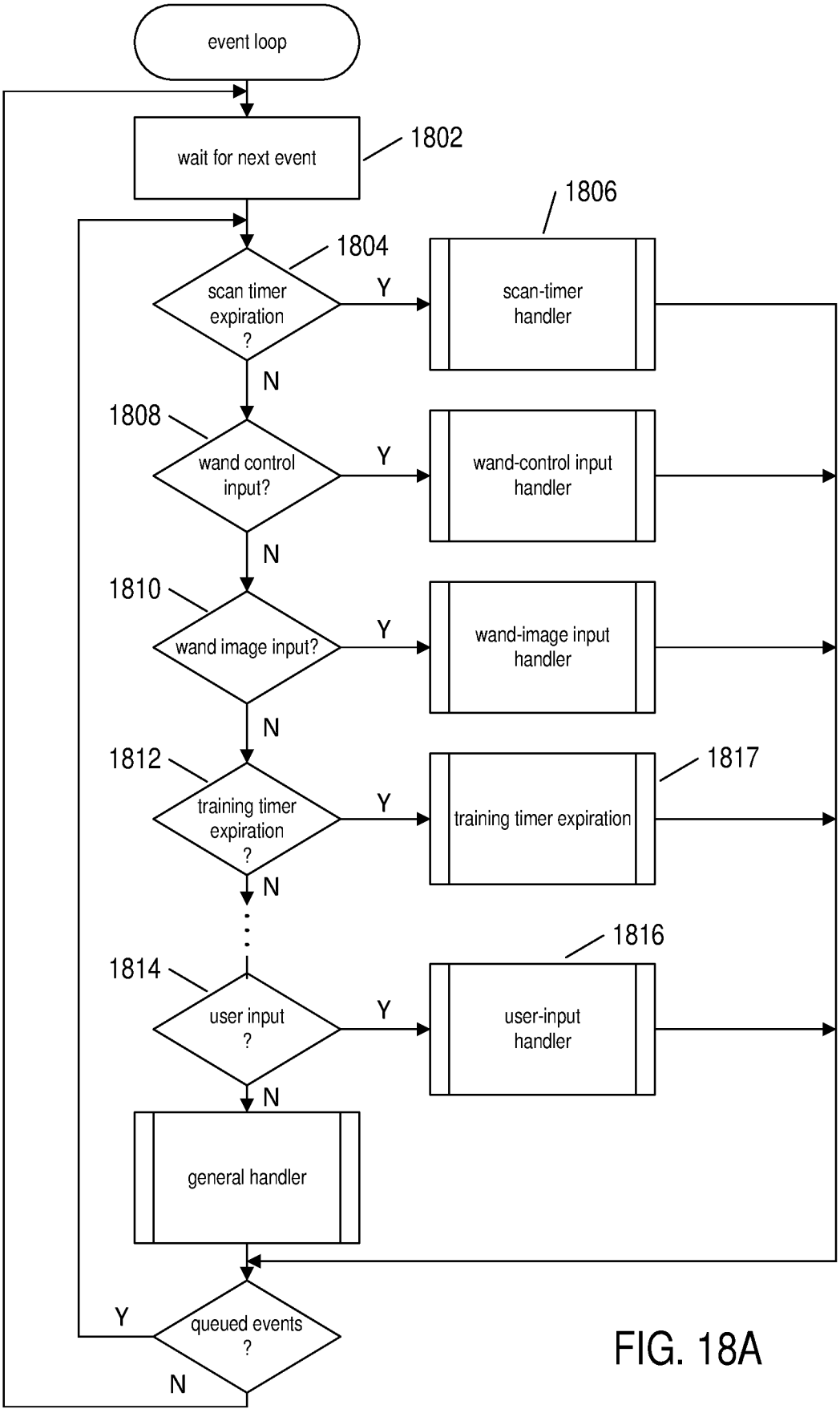
event loop
wait for next event
1802
1806
1804
scan timer expiration ?
Y
scan-timer handler
N
1808
wand control input?
Y
wand-control input handler
N
1810
wand image input?
Y
wand-image input handler
N
1812
training timer expiration ?
Y
training timer expiration
1817
N
1816
1814
user input ?
Y
user-input handler
N
general handler
Y
queued events ?
N

FIG. 18A

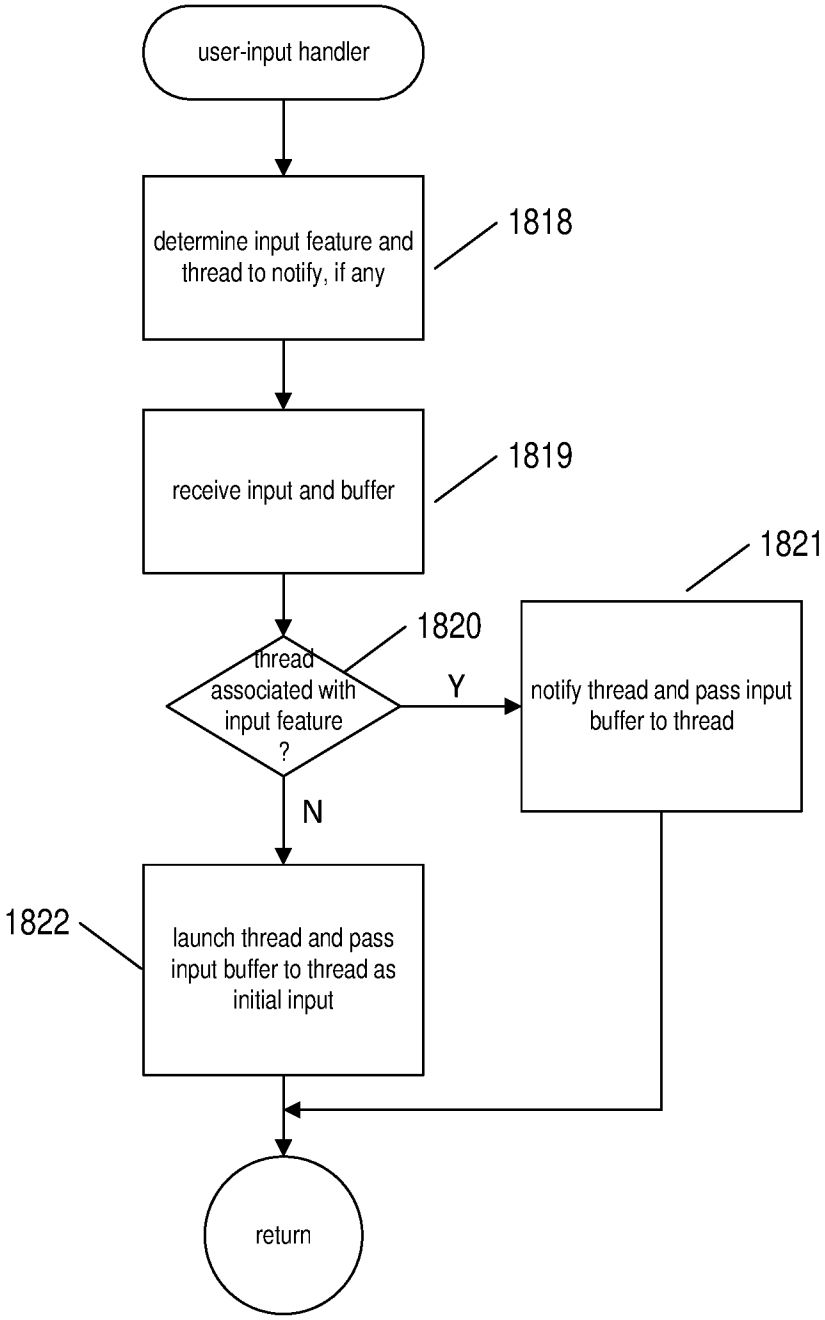
user-input handler
determine input feature and thread to notify, if any
1818
receive input and buffer
1819
1821
1820
thread associated with input feature ?
Y
notify thread and pass input buffer to thread
N
1822
launch thread and pass input buffer to thread as initial input
return

FIG. 18B

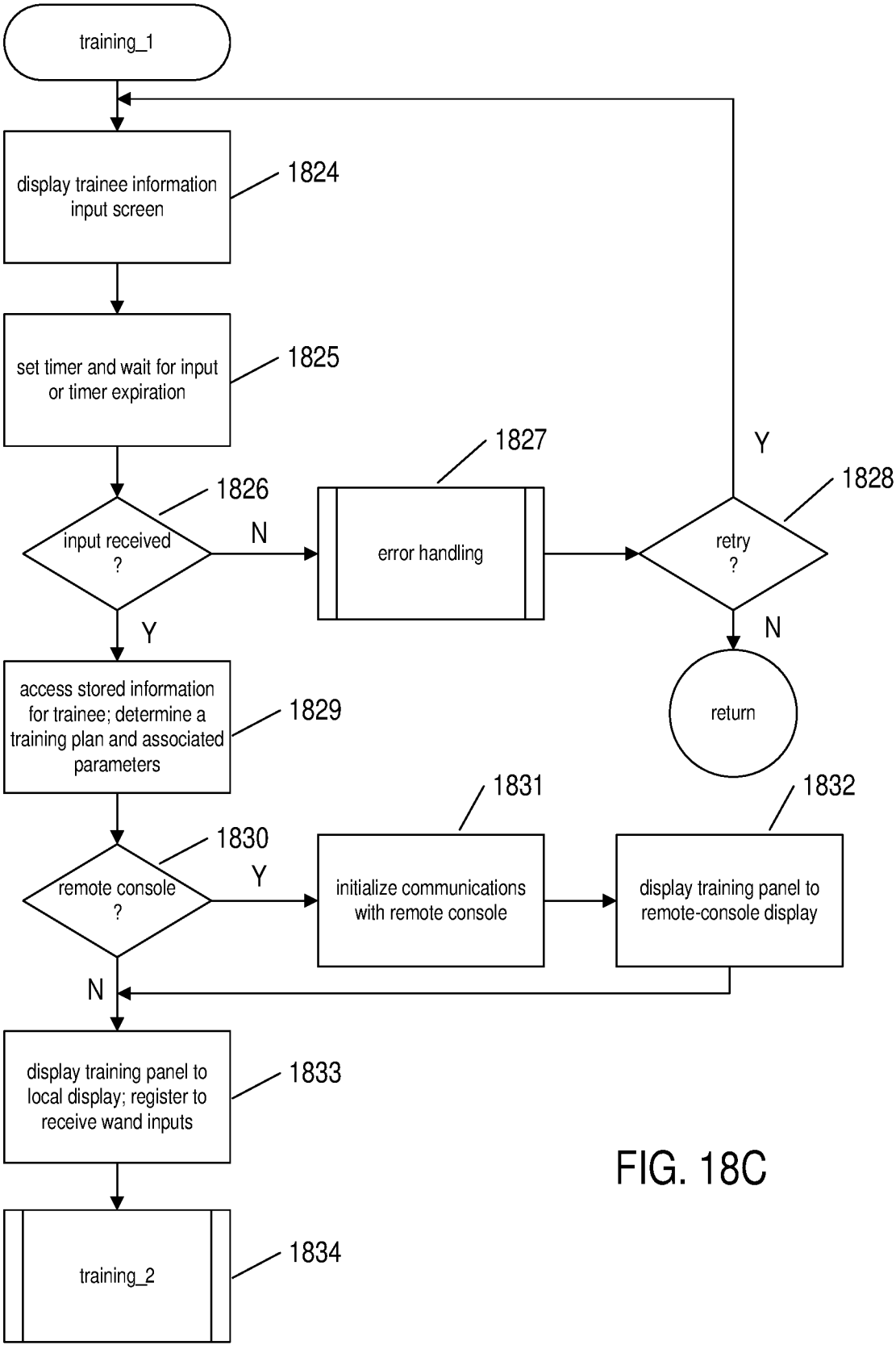
training_1
display trainee information input screen
1824
set timer and wait for input or timer expiration
1825
1826
input received ?
N
1827
error handling
Y
1828
retry ?
N
return
Y
access stored information for trainee; determine a training plan and associated parameters
1829
1830
remote console ?
Y
1831
initialize communications with remote console
1832
display training panel to remote-console display
N
display training panel to local display; register to receive wand inputs
1833
training_2
1834

FIG. 18C

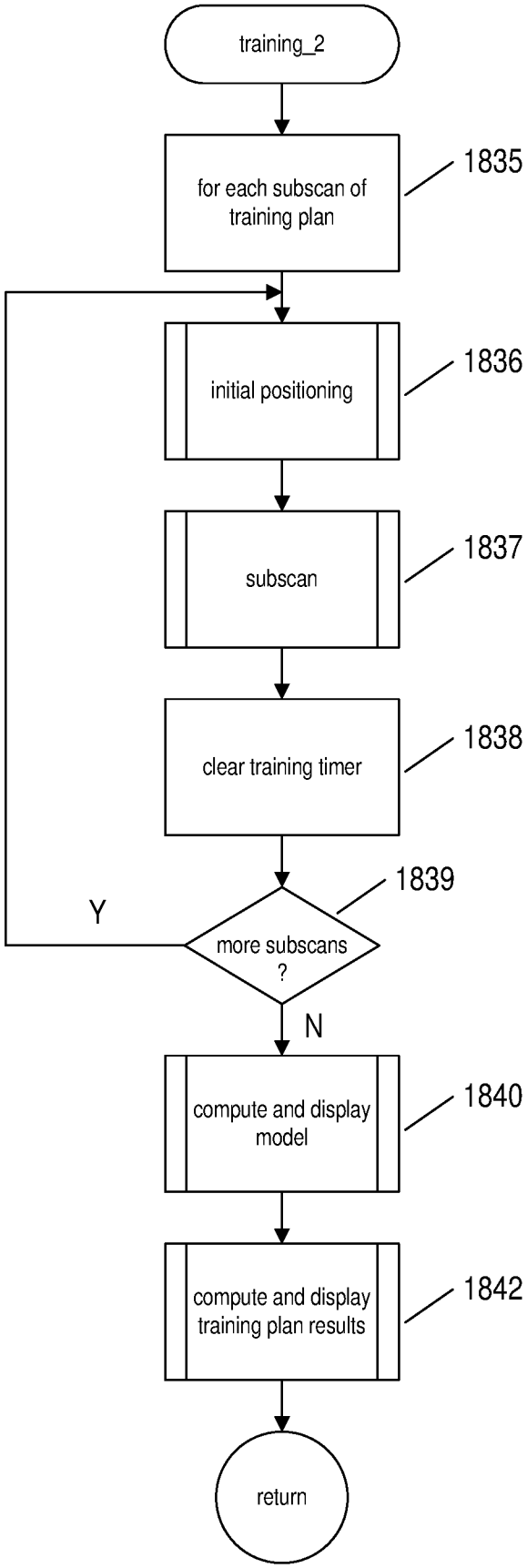
training_2
for each subscan of training plan
1835
initial positioning
1836
subscan
1837
clear training timer
1838
more subscans ?
1839
Y
N
compute and display model
1840
compute and display training plan results
1842
return

FIG. 18D

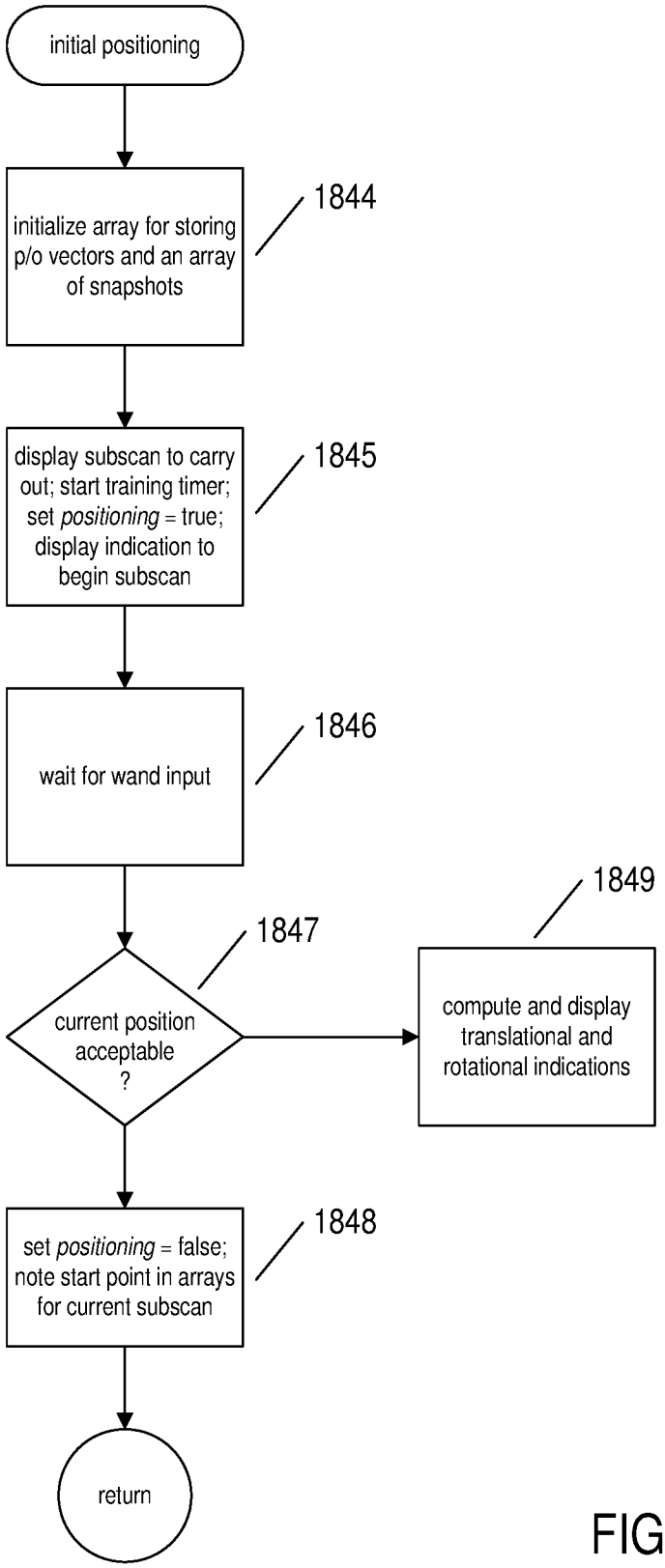
initial positioning
initialize array for storing p/o vectors and an array of snapshots
1844
display subscan to carry out; start training timer; set *positioning* = true; display indication to begin subscan
1845
wait for wand input
1846
current position acceptable ?
1847
compute and display translational and rotational indications
1849
set *positioning* = false; note start point in arrays for current subscan
1848
return

FIG. 18E

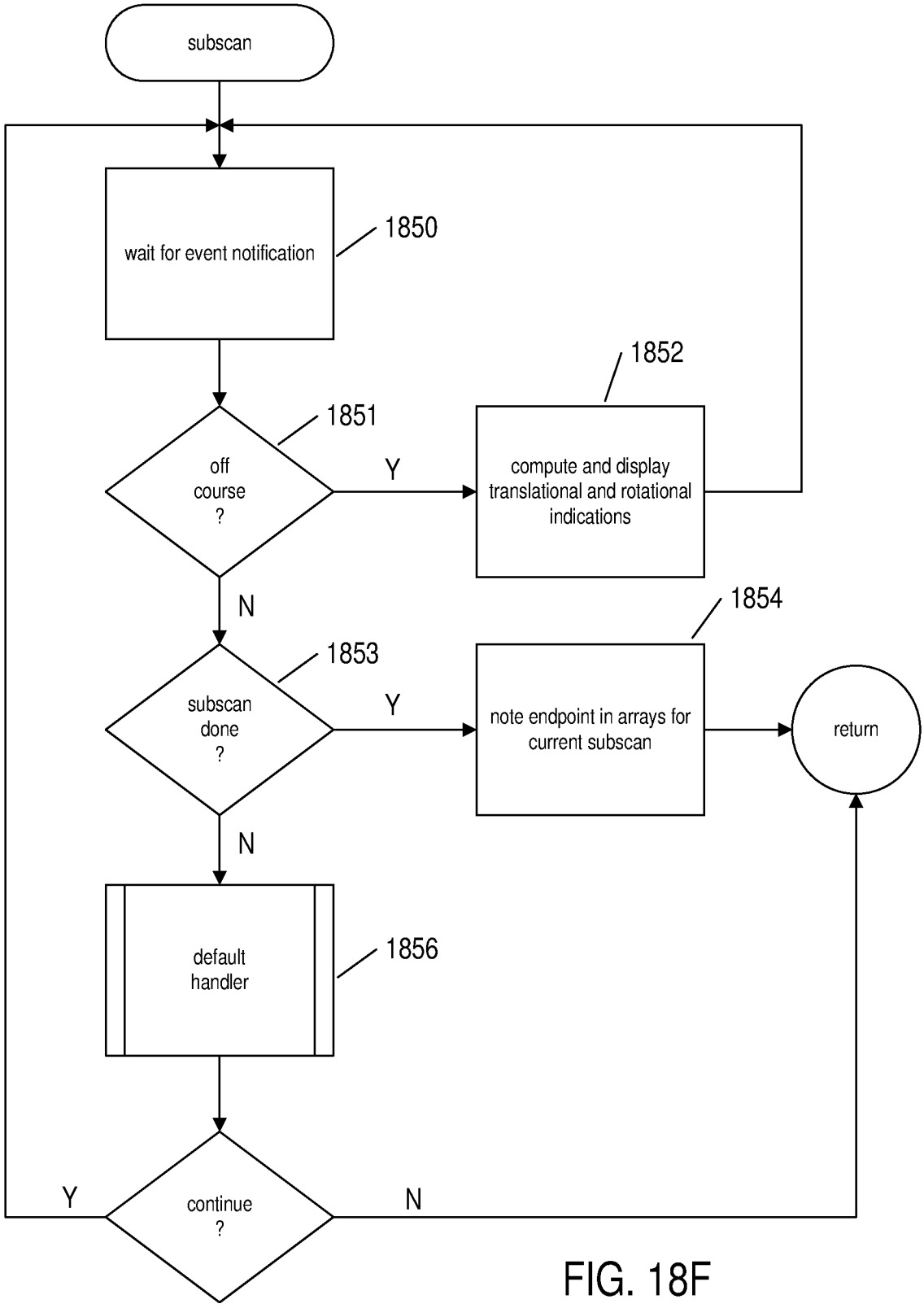
subscan
wait for event notification
1850
1852
1851
off course ?
Y
compute and display translational and rotational indications
N
1854
1853
subscan done ?
Y
note endpoint in arrays for current subscan
return
N
default handler
1856
Y
continue ?
N

FIG. 18F

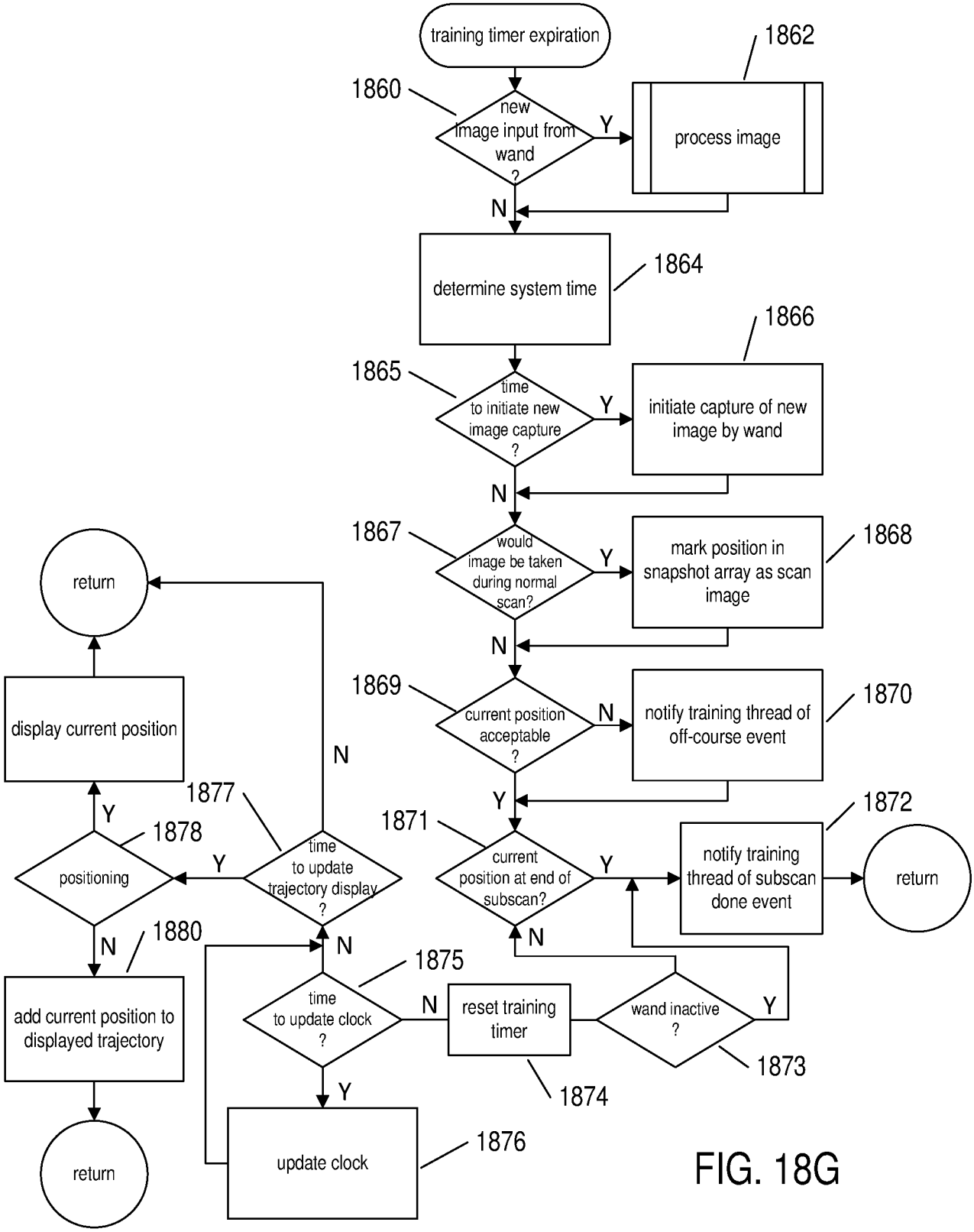
training timer expiration
1862
1860
new image input from wand ?
Y
process image
N
determine system time
1864
1866
1865
time to initiate new image capture ?
Y
initiate capture of new image by wand
N
1867
would image be taken during normal scan?
Y
mark position in snapshot array as scan image
1868
N
1869
current position acceptable ?
N
notify training thread of off-course event
1870
Y
1871
current position at end of subscan?
Y
notify training thread of subscan done event
1872
return
N
wand inactive ?
Y
1873
reset training timer
1874
N
1875
time to update clock ?
N
Y
update clock
1876
1877
time to update trajectory display ?
N
1878
positioning
Y
Y
display current position
return
N
1880
add current position to displayed trajectory
return

FIG. 18G

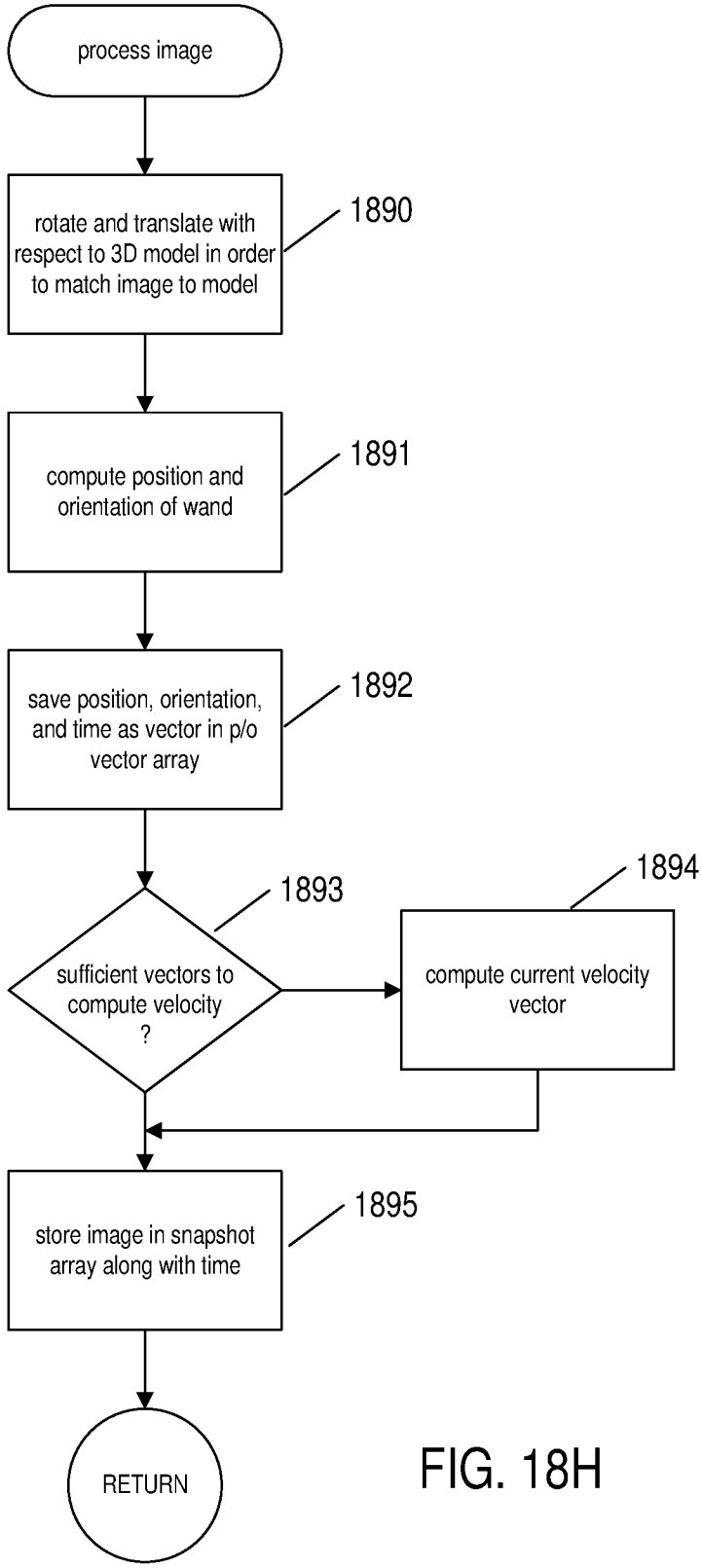
process image
rotate and translate with respect to 3D model in order to match image to model
1890
compute position and orientation of wand
1891
save position, orientation, and time as vector in p/o vector array
1892
sufficient vectors to compute velocity ?
1893
compute current velocity vector
1894
store image in snapshot array along with time
1895
RETURN

FIG. 18H

INTERNATIONAL SEARCH REPORT

International application No
PCT/IB2016/050333

A. CLASSIFICATION OF SUBJECT MATTER
INV. G09B23/28 A61C9/00
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
G09B A61C

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
EPO-Internal, WPI Data, INSPEC

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2014/120493 A1 (LEVIN ADI [IL]) 1 May 2014 (2014-05-01) paragraphs [0014] - [0075]	1-21
X	US 2001/038705 A1 (RUBBERT RUDGER [DE] ET AL) 8 November 2001 (2001-11-08) paragraphs [0140] - [0392]	1-21
X	US 2009/061381 A1 (DURBIN DUANE MILFORD [US] ET AL) 5 March 2009 (2009-03-05) paragraphs [0029] - [0051]	1-21
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[X] Further documents are listed in the continuation of Box C.

[X] See patent family annex.

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"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
19 April 2016	28/04/2016

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Díaz de Lezana, C

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INTERNATIONAL SEARCH REPORT

International application No
PCT/IB2016/050333

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

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A	ROBERT G. NEDELCU ET AL: "Scanning accuracy and precision in 4 intraoral scanners: An in vitro comparison based on 3-dimensional analysis", JOURNAL OF PROSTHETIC DENTISTRY., vol. 112, no. 6, 1 December 2014 (2014-12-01), pages 1461-1471, XP055265472, AMSTERDAM, NL ISSN: 0022-3913, DOI: 10.1016/j.prosdent.2014.05.027 the whole document	1-21

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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/IB2016/050333

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