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Franck et al.

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(54) **REMOVABLE FRAMES FOR
STEREOTACTIC LOCALIZATION**

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- Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

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- (52) **U.S. Cl.** **606/130**
- (58) **Field of Search** 606/130; 600/378;
607/116, 139

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(74) *Attorney, Agent, or Firm*—Fish & Richardson P.C.

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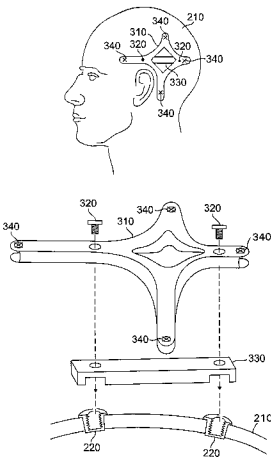
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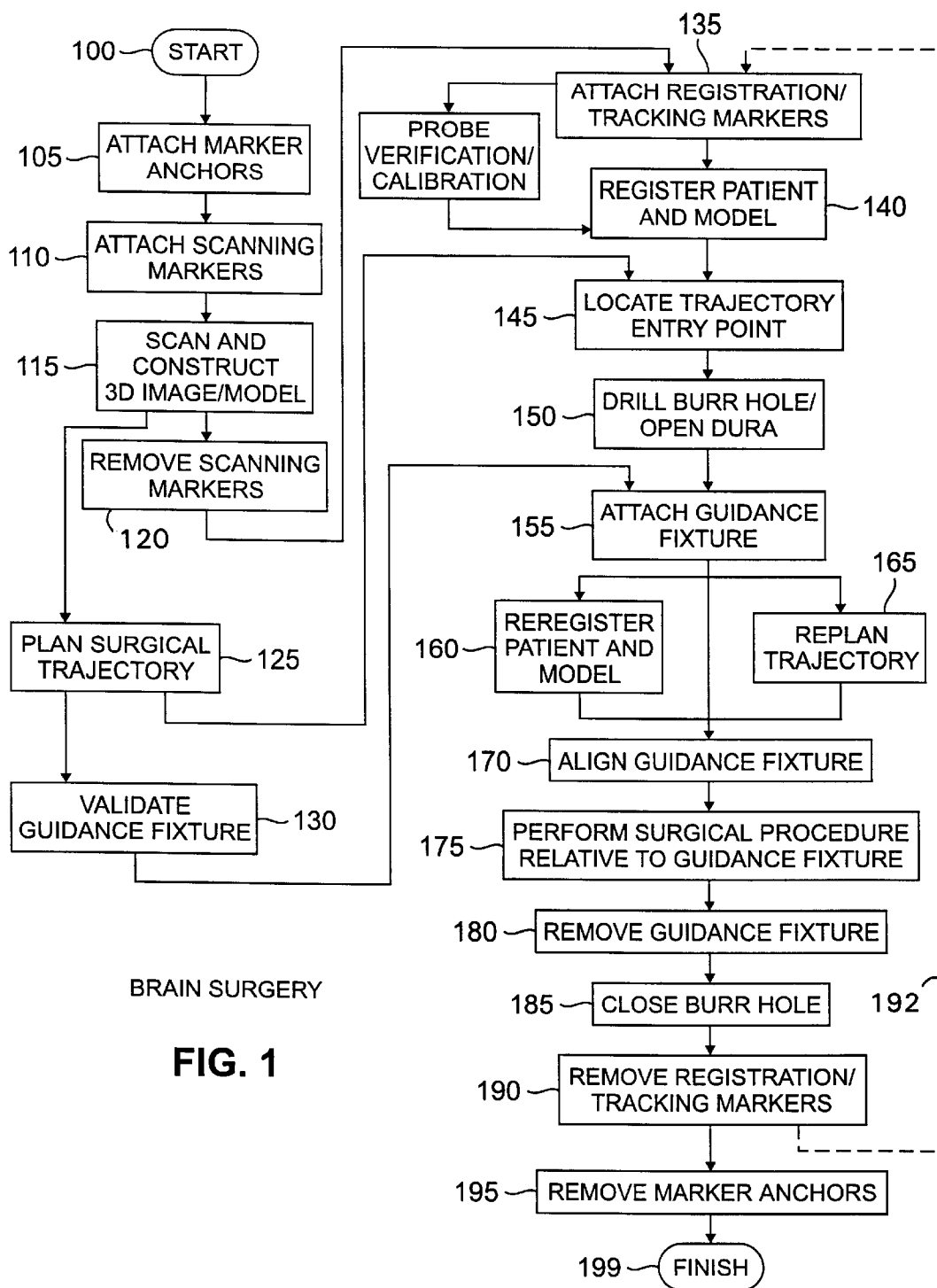
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(57) **ABSTRACT**

A marking and tracking apparatus for stereotactic surgery on a body. The apparatus includes a rigid scanning frame. The scanning frame includes a set of scanning markers for making corresponding images in a scanned image of the body, and multiple mounting points, such that when the scanning frame is attached to the body, each of the mounting points mates with a corresponding one of multiples anchors, such as threaded inserts, embedded in the body. The apparatus can also include a rigid tracking frame. The tracking frame includes a set of tracking markers for tracking a position of the frame using a remote sensing device, and multiple mounting points, such that when the tracking frame is attached to the body, each of the mounting points mates with a corresponding one of the anchors embedded in the body.

16 Claims, 27 Drawing Sheets





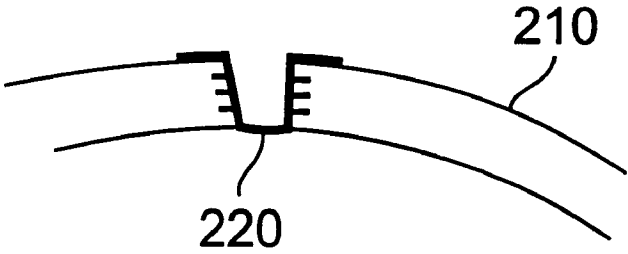
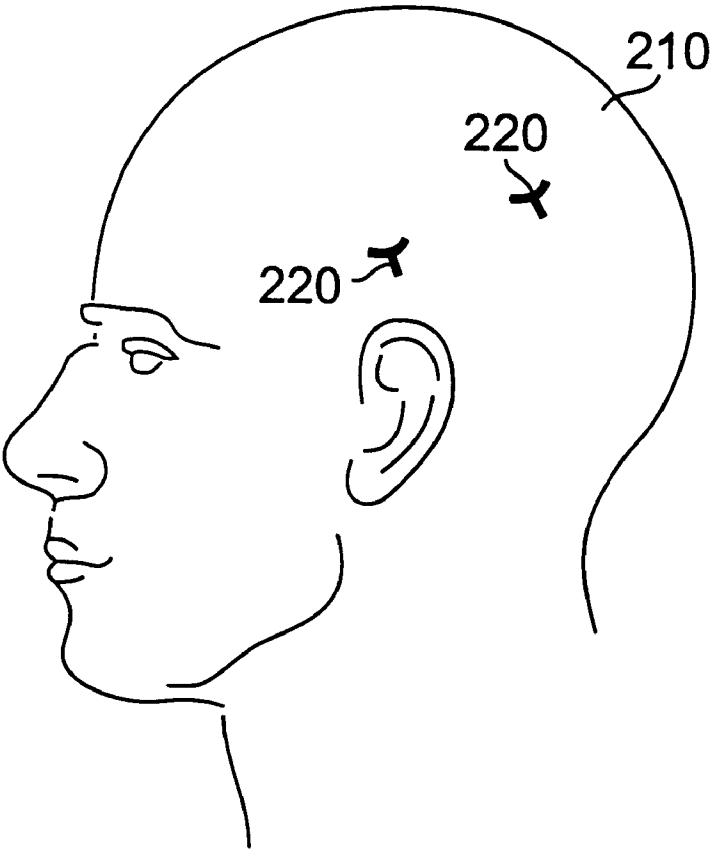


FIG. 2

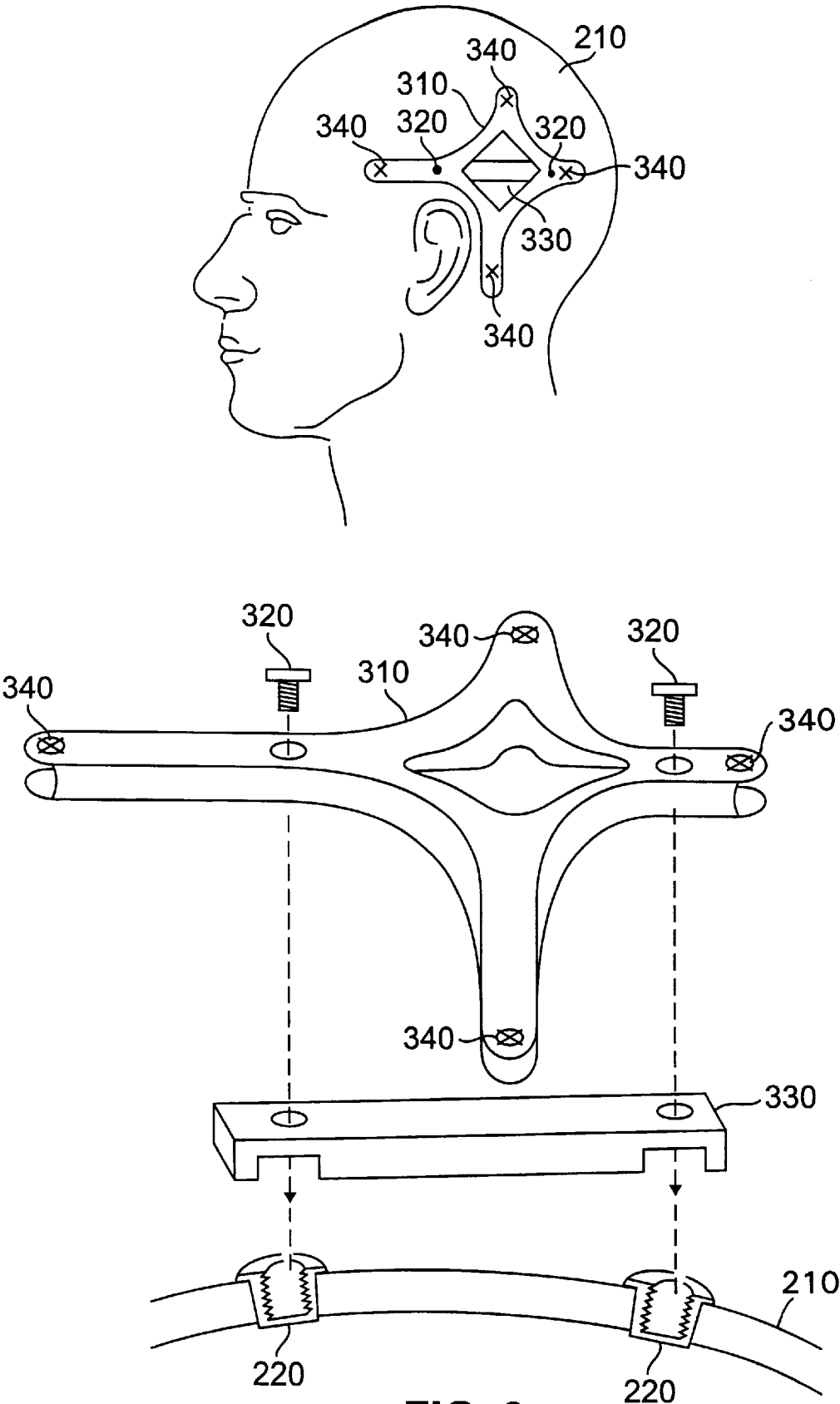


FIG. 3

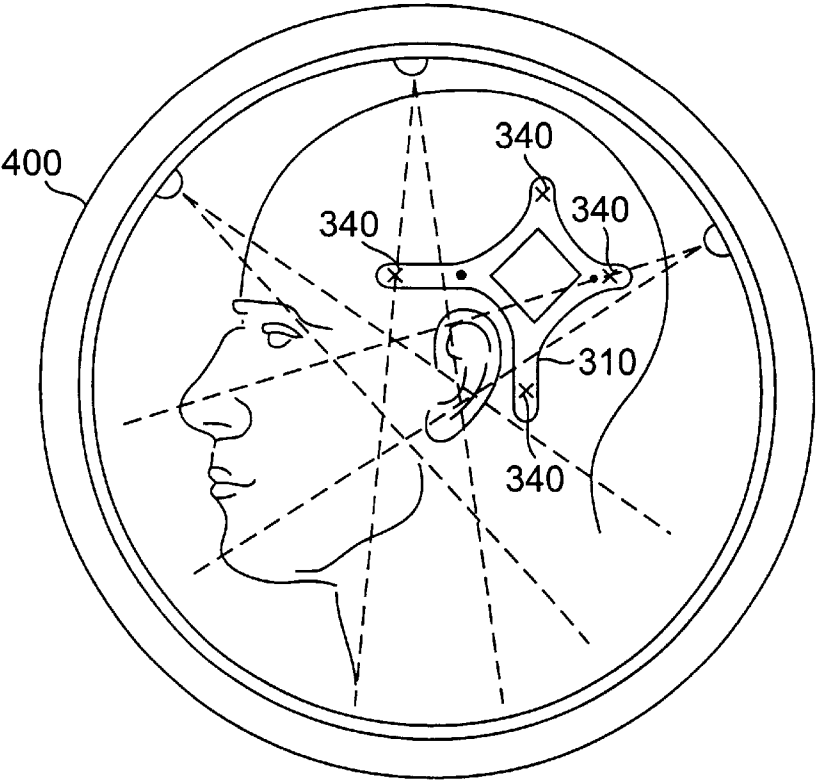
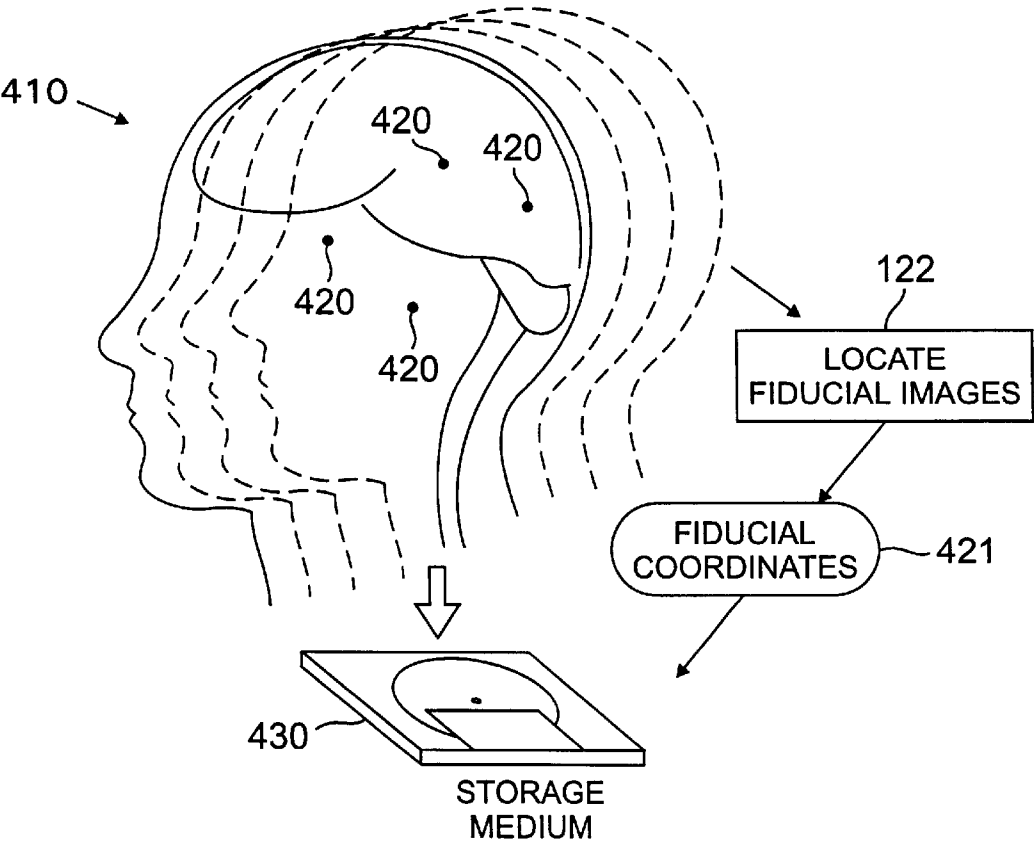


FIG. 4



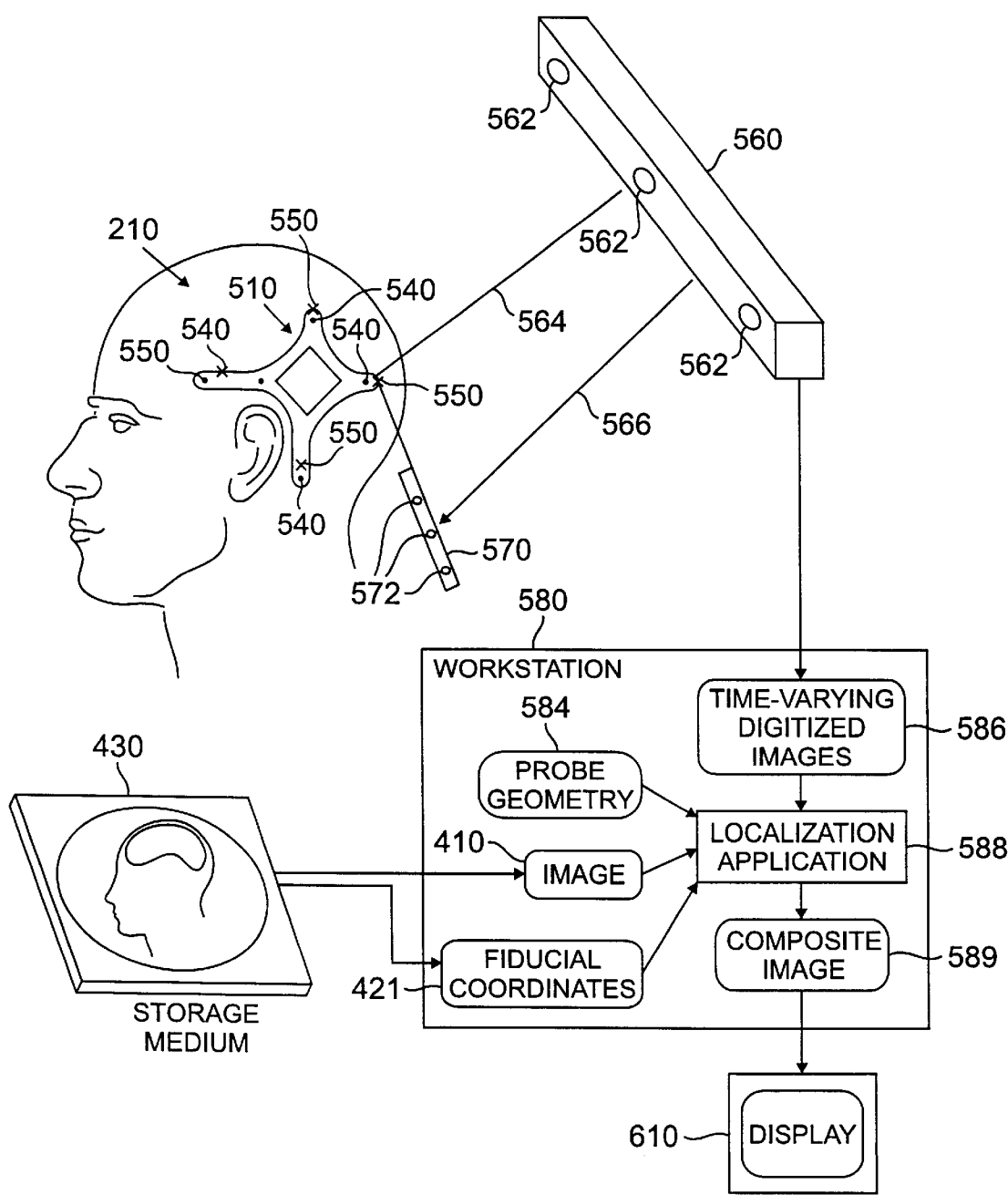


FIG. 5

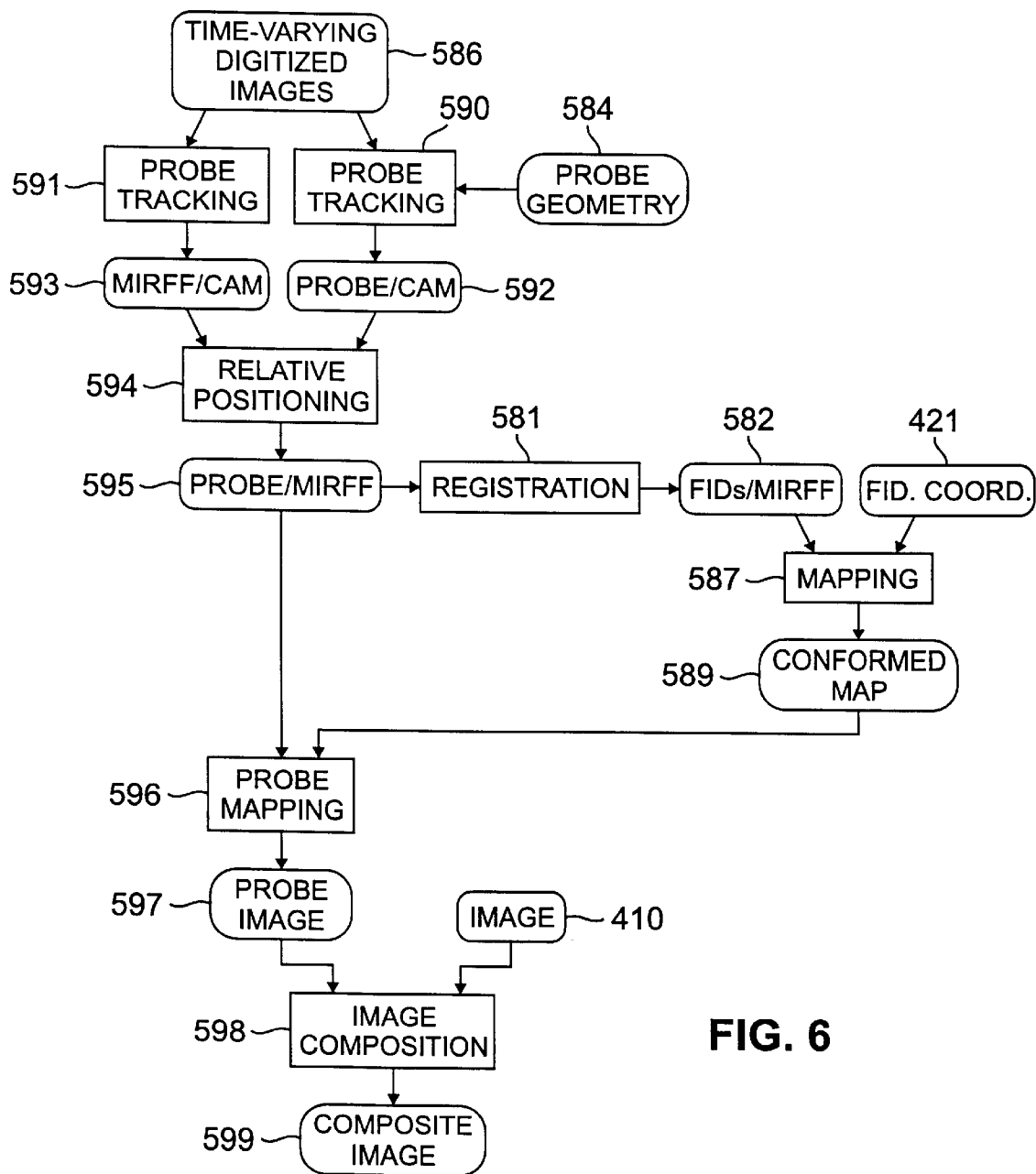


FIG. 6

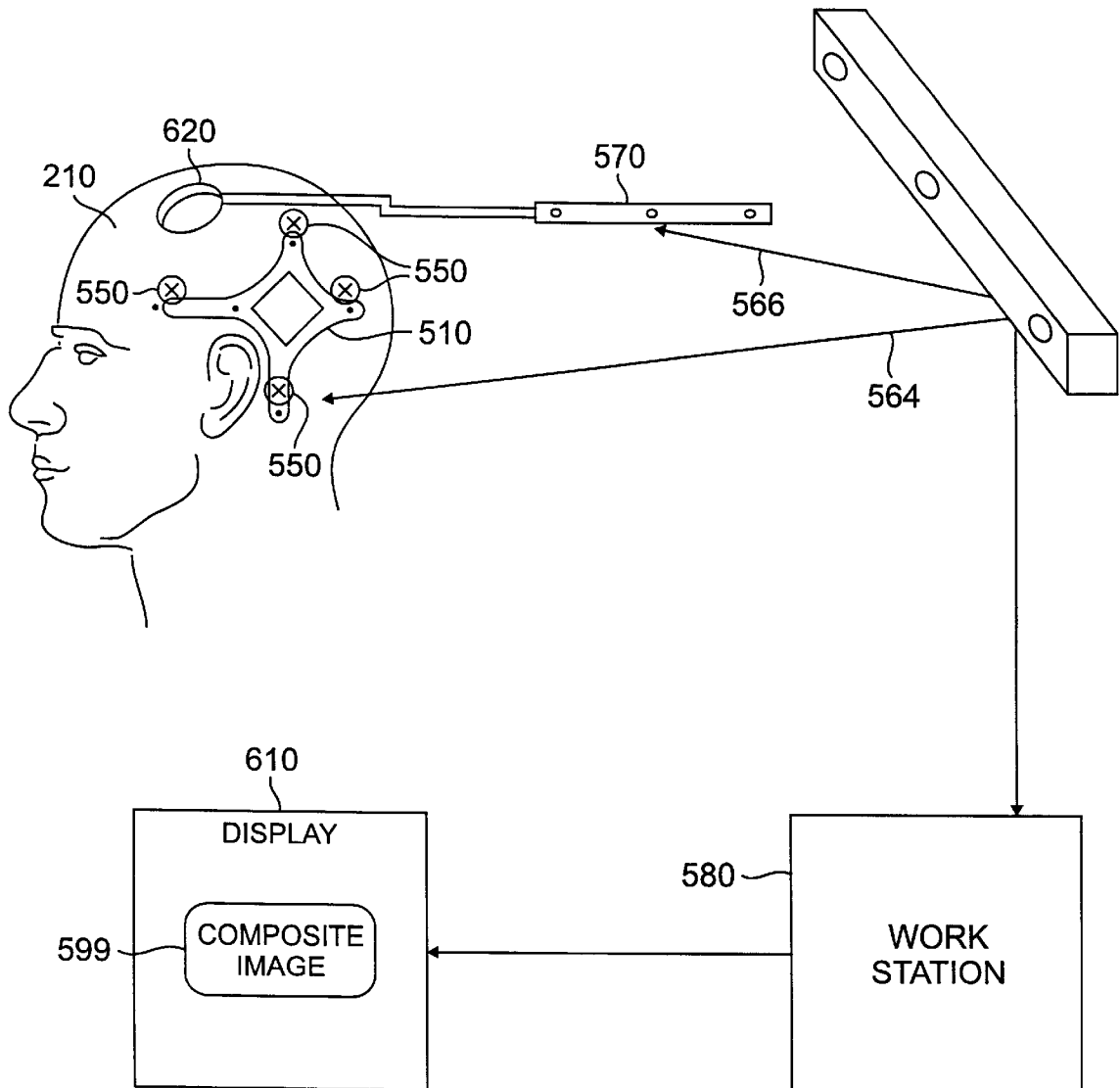


FIG. 7

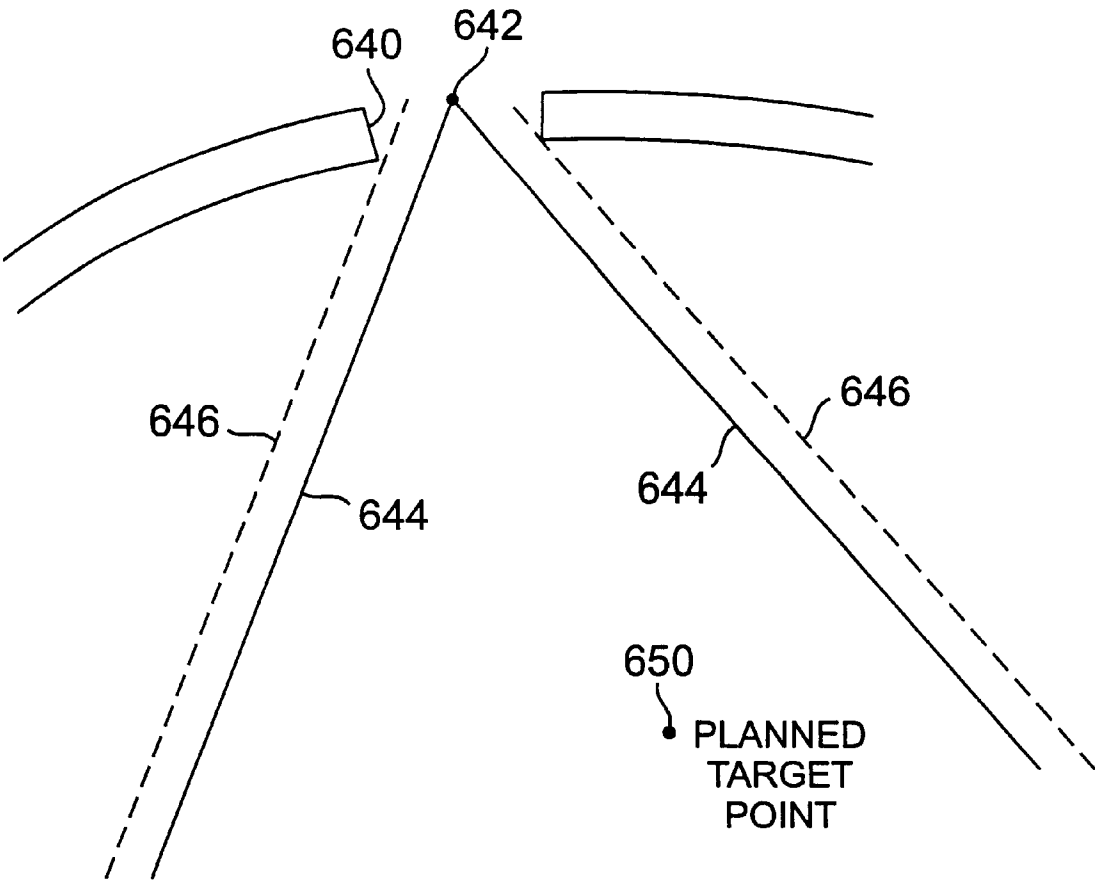


FIG. 8

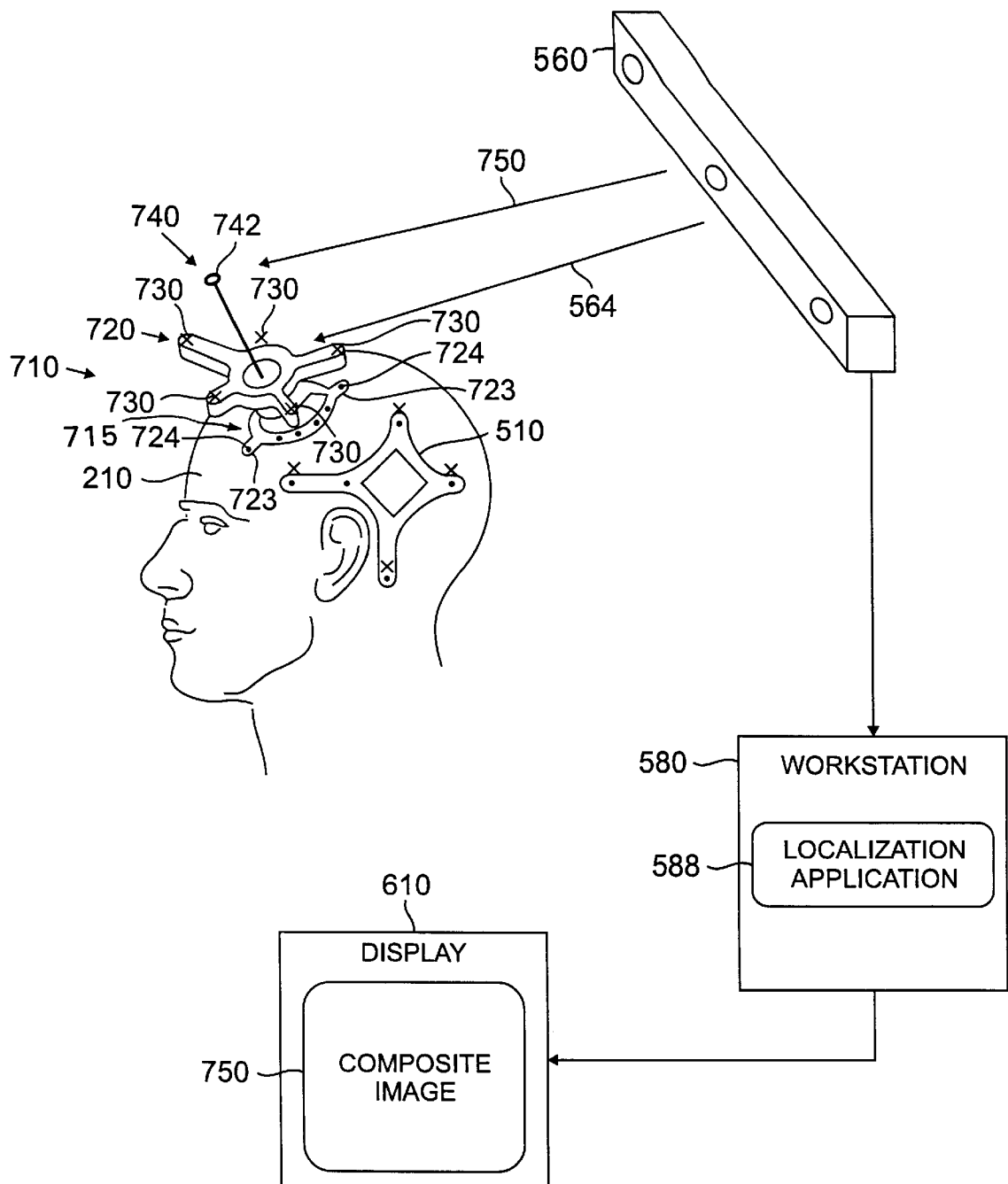


FIG. 9

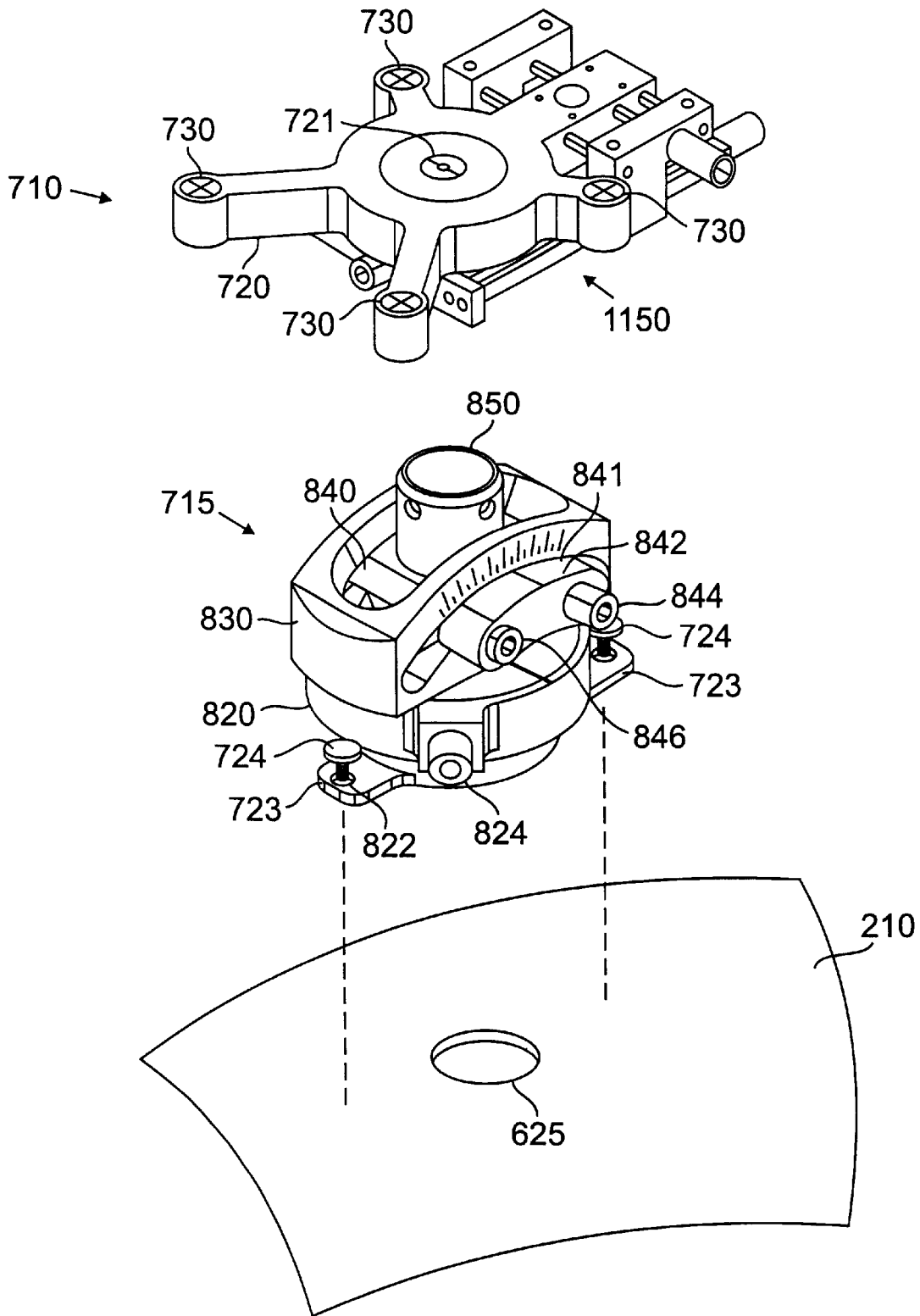
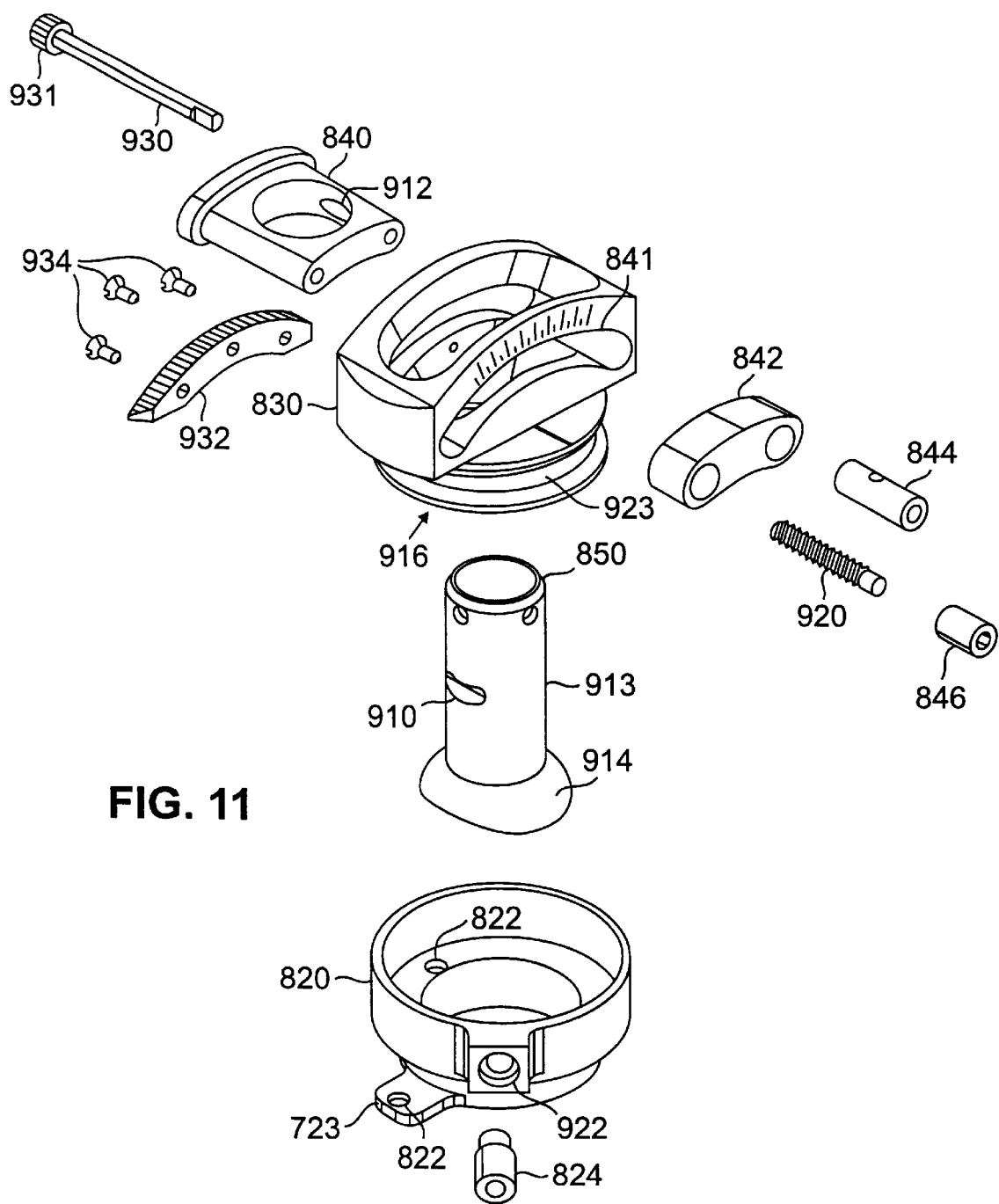
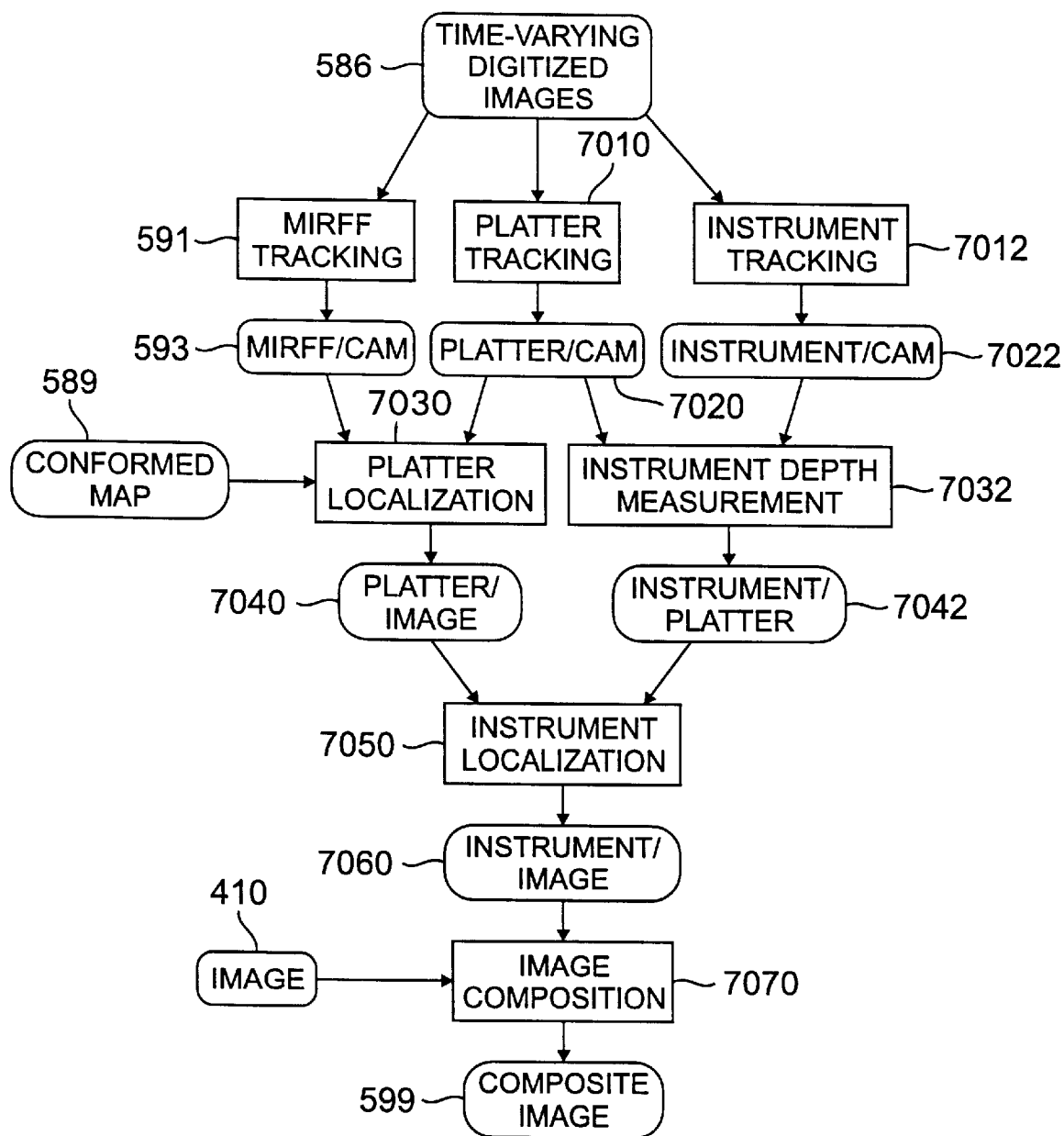
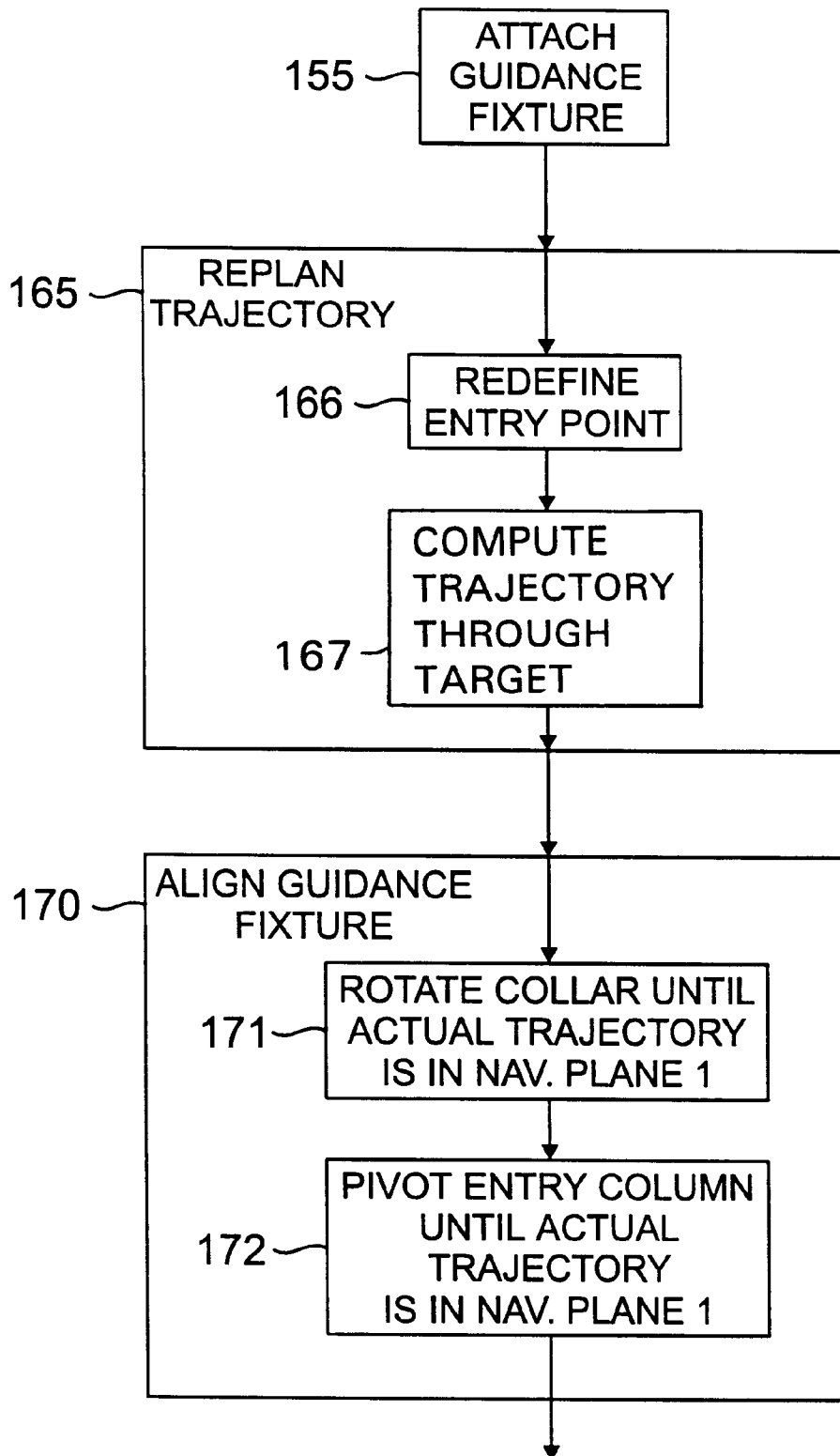


FIG. 10



**FIG. 12**

**FIG. 13**

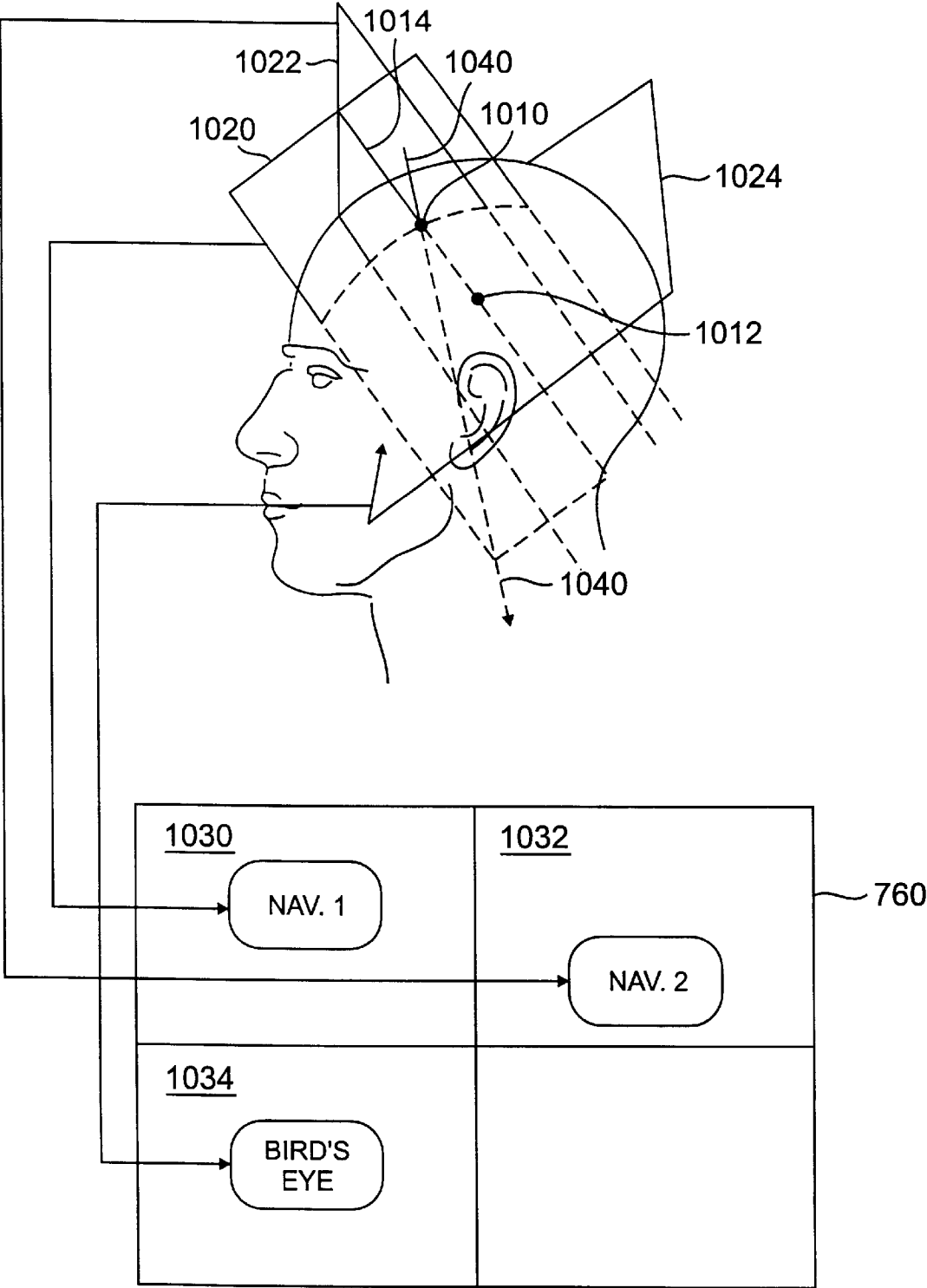


FIG. 14a

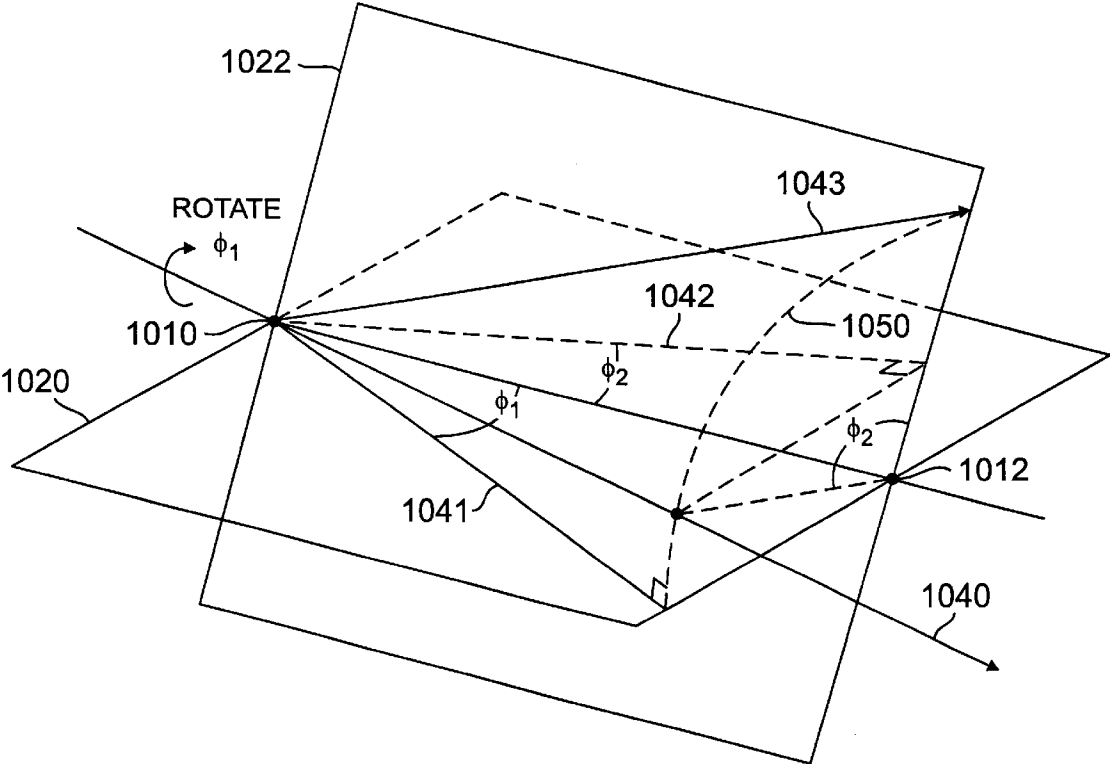


FIG. 14b

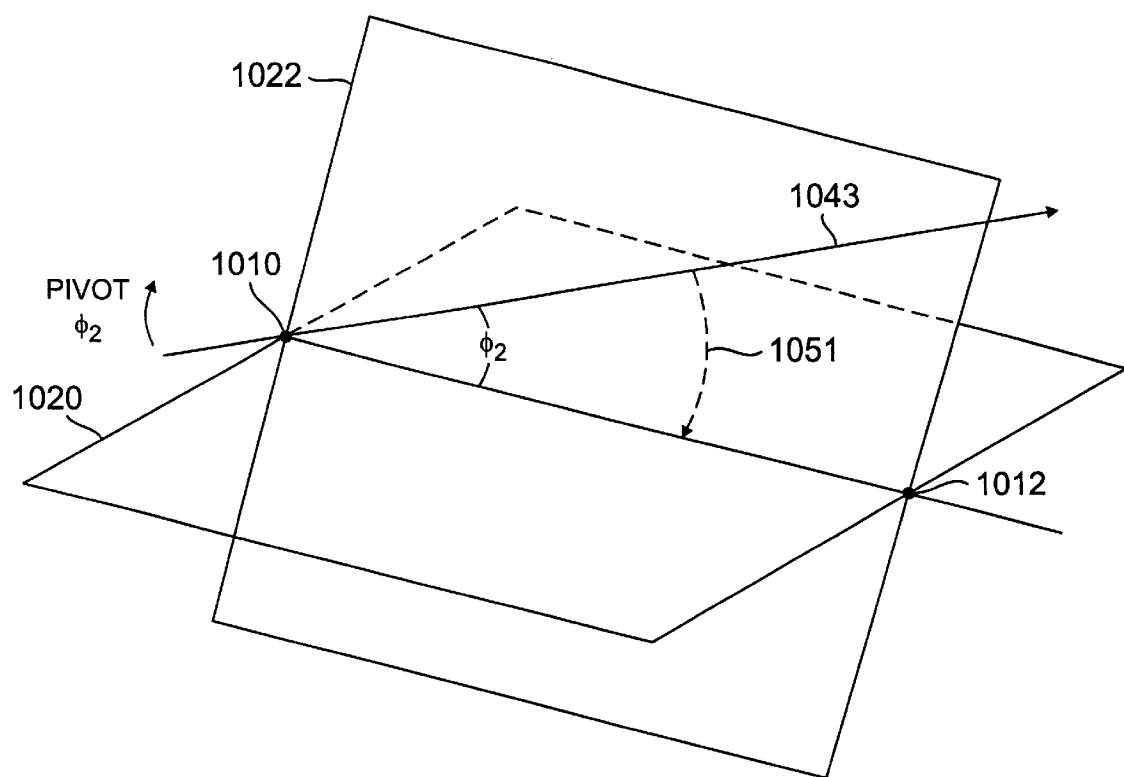


FIG. 14c

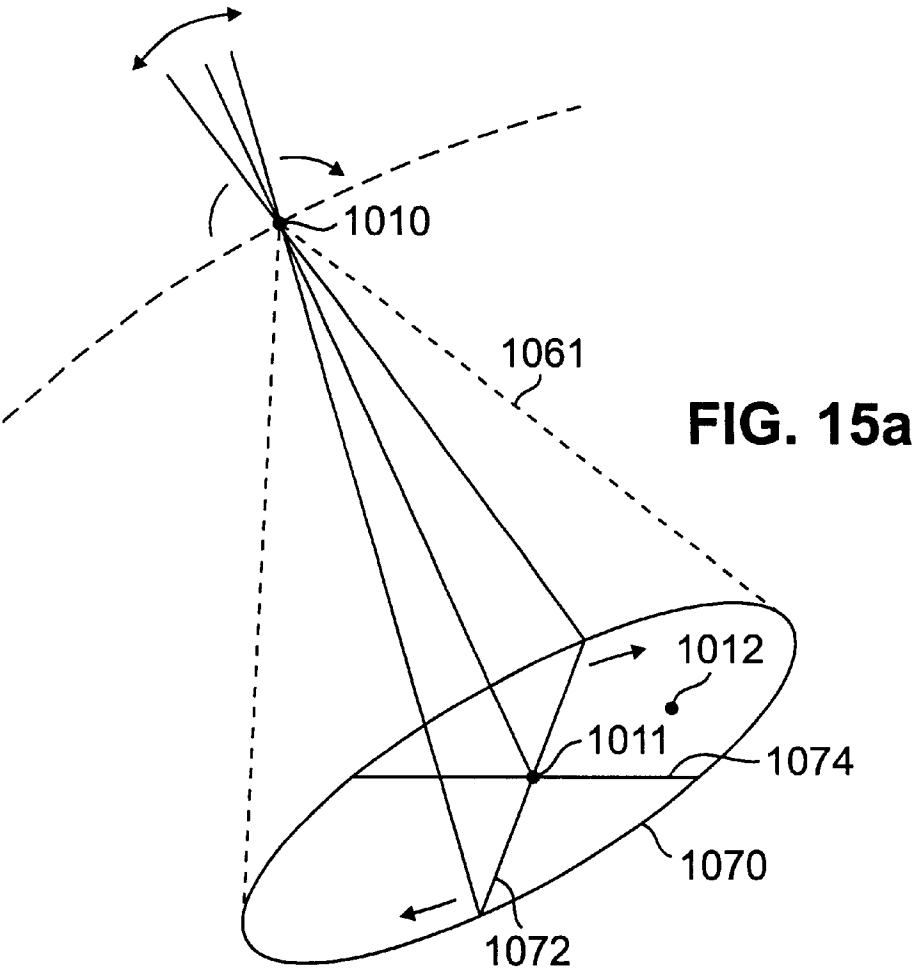
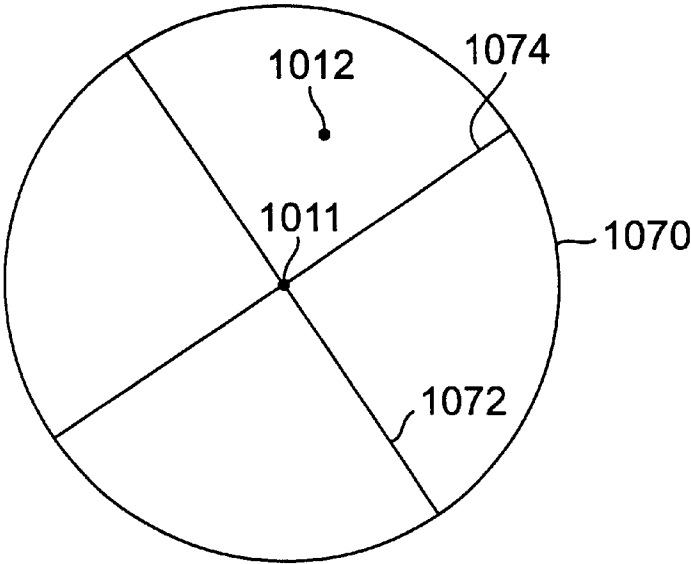


FIG. 15b



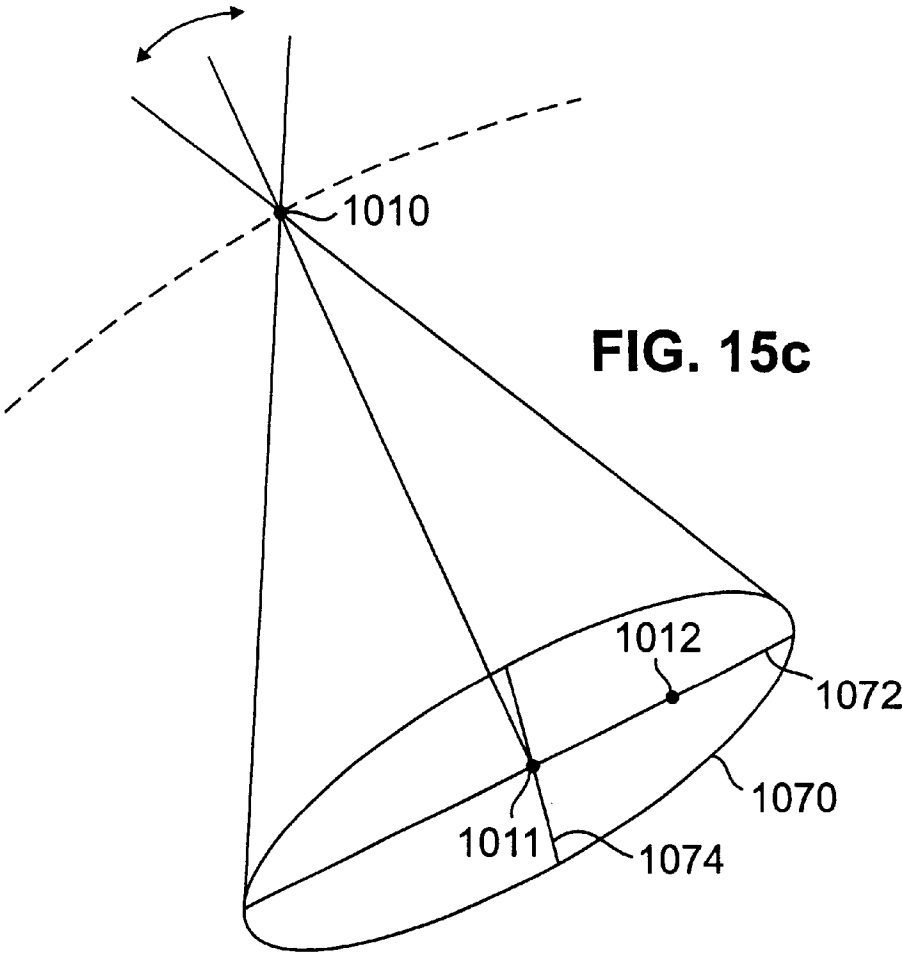
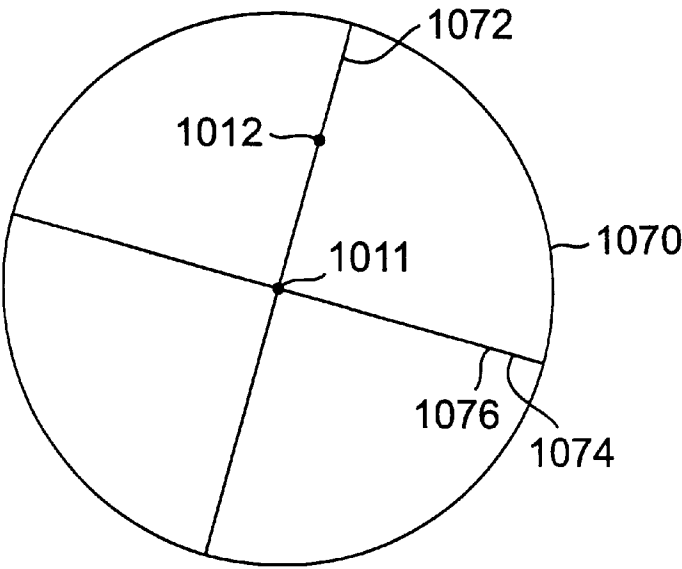


FIG. 15d



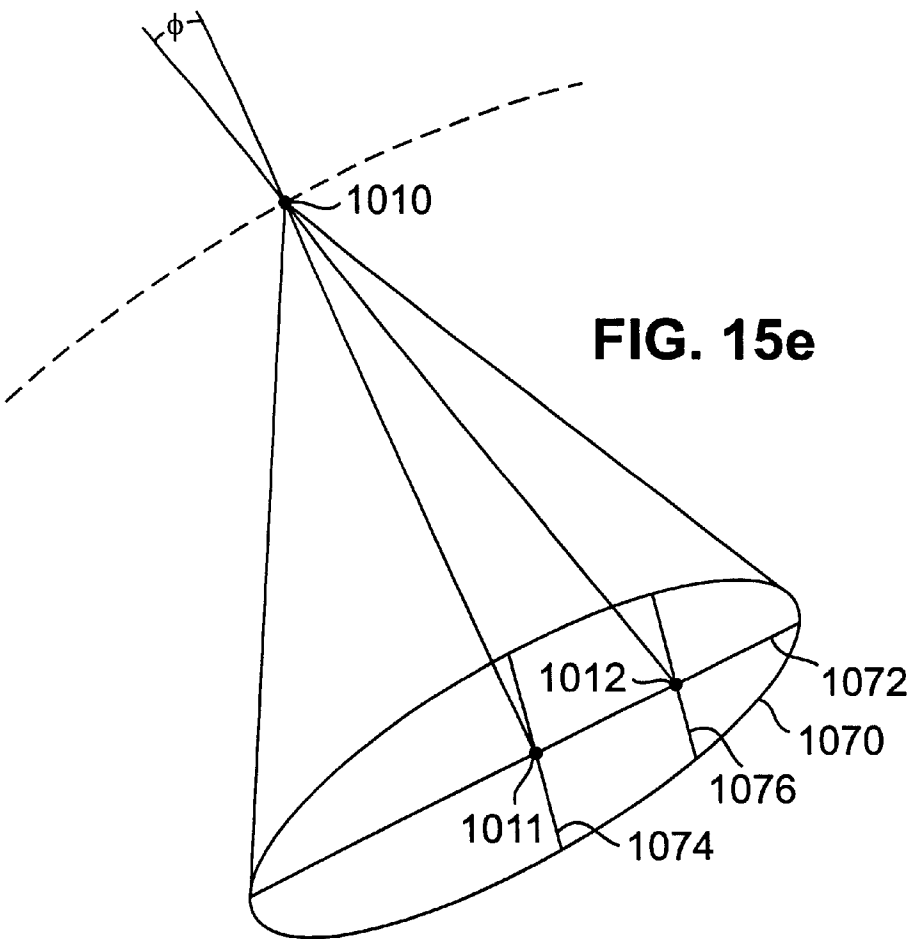
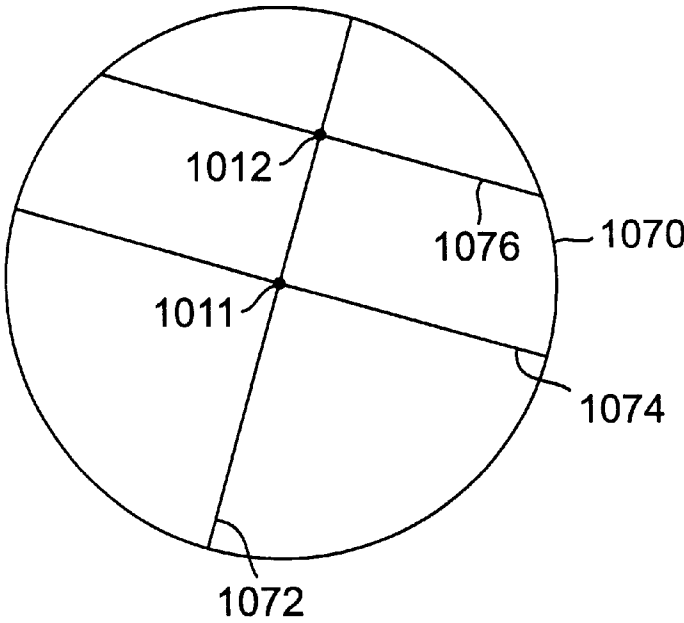


FIG. 15f



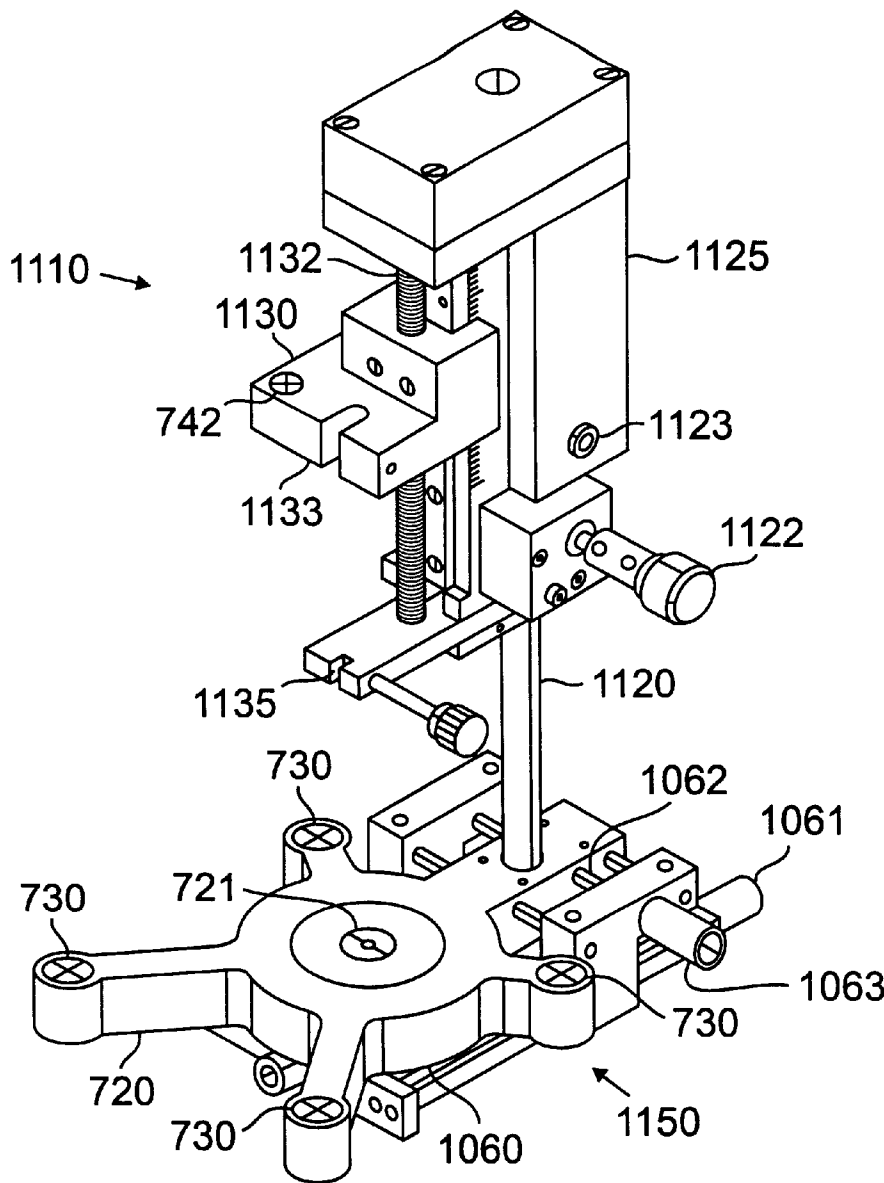
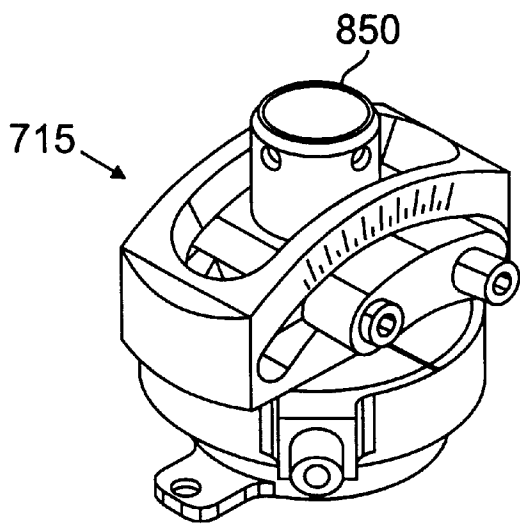


FIG. 16



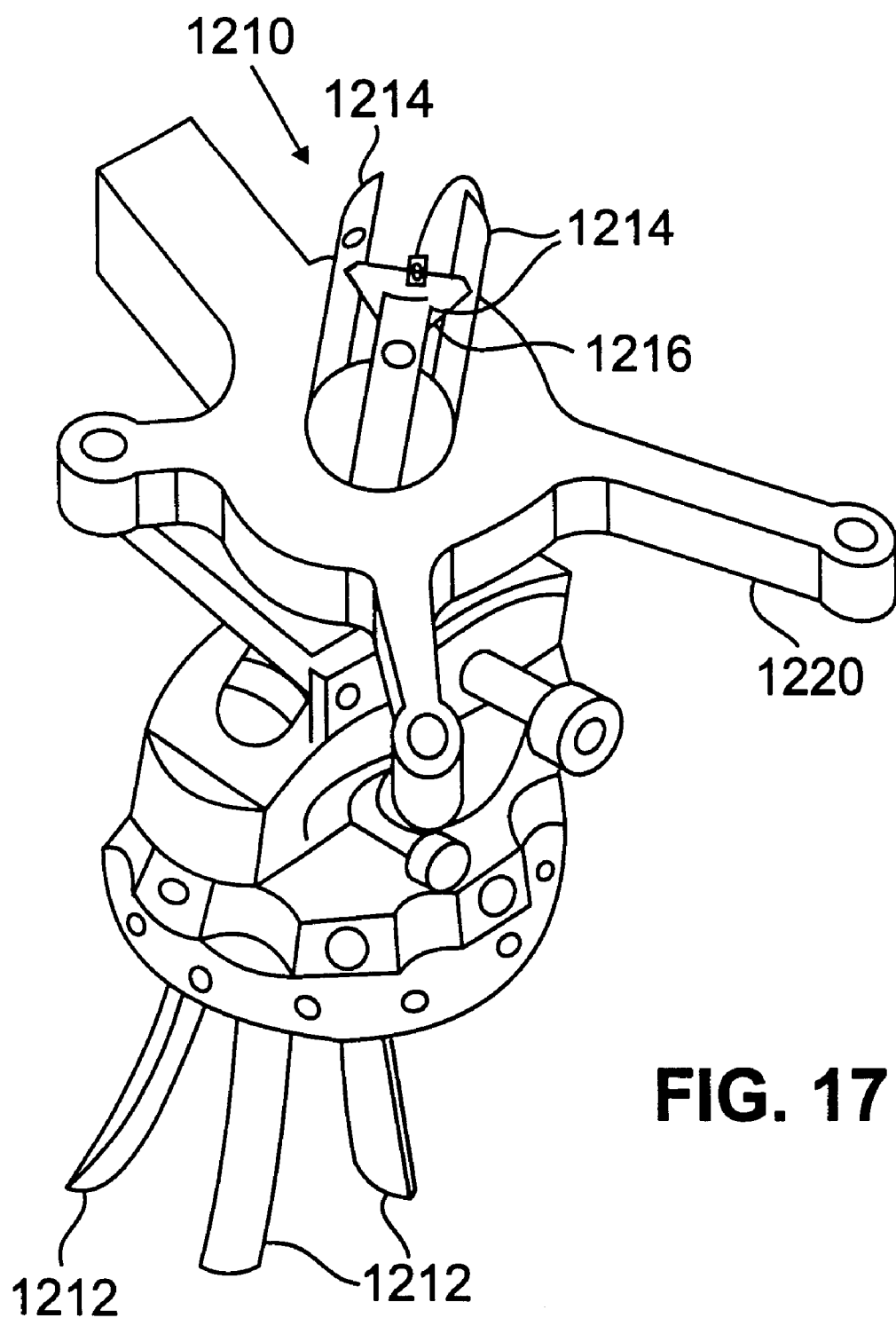
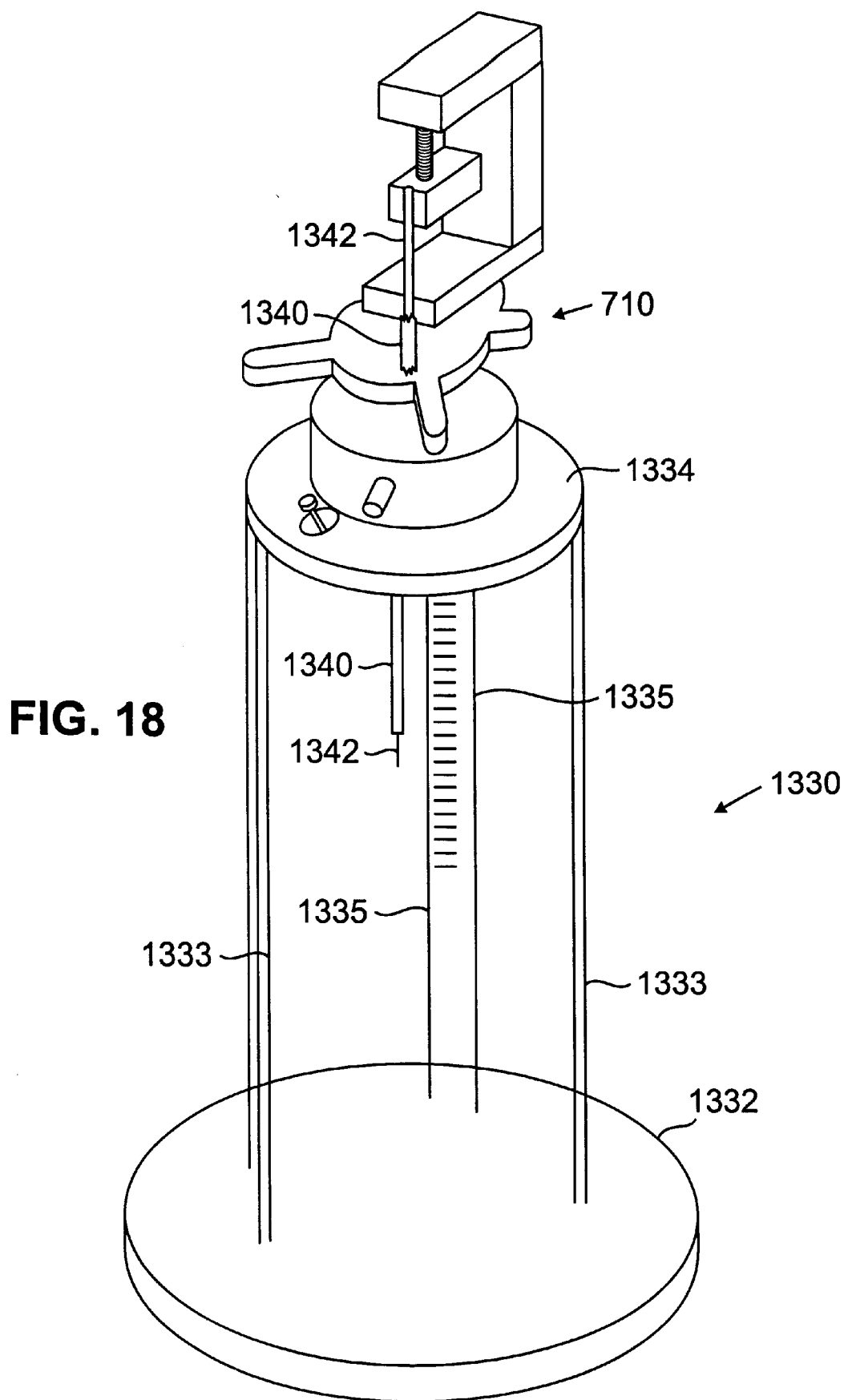


FIG. 17



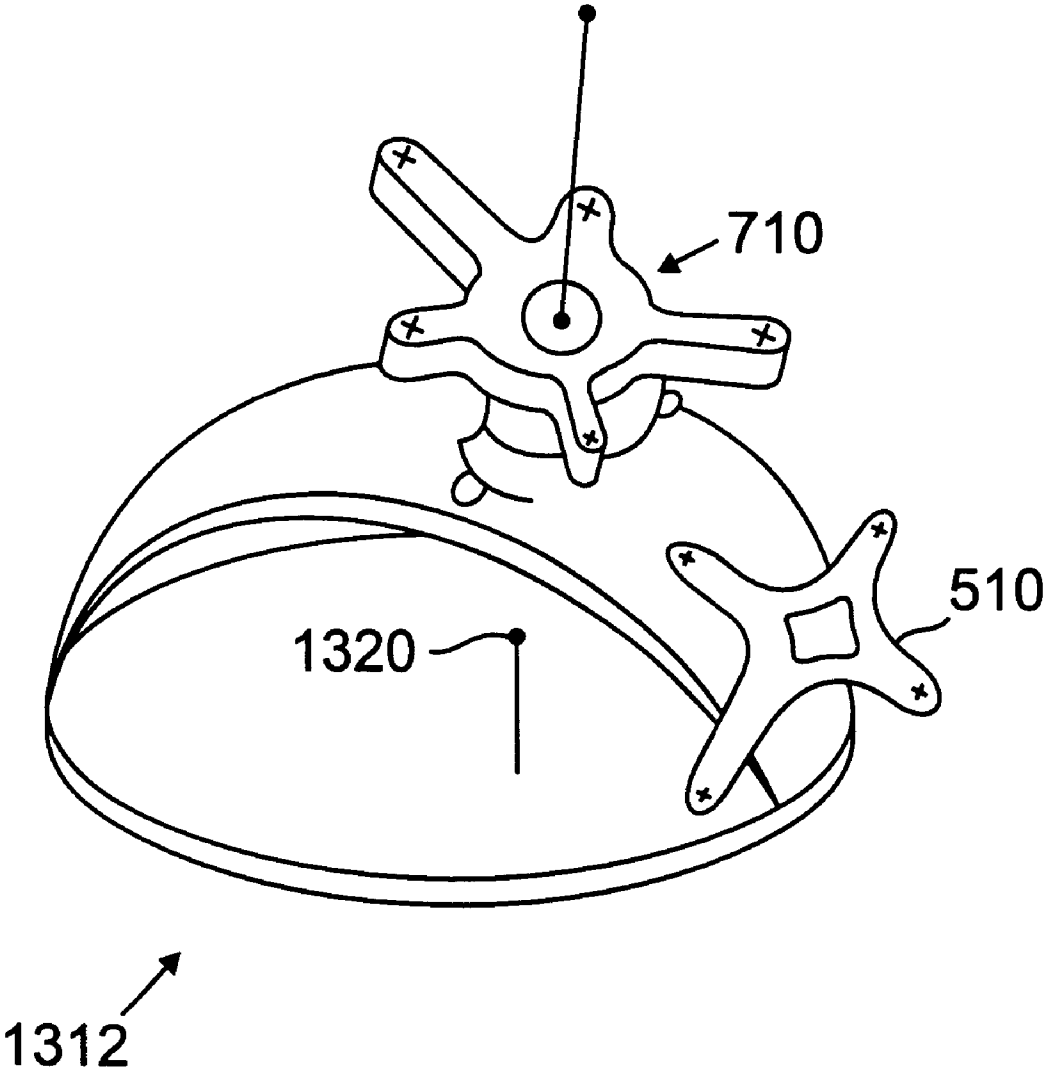


FIG. 19

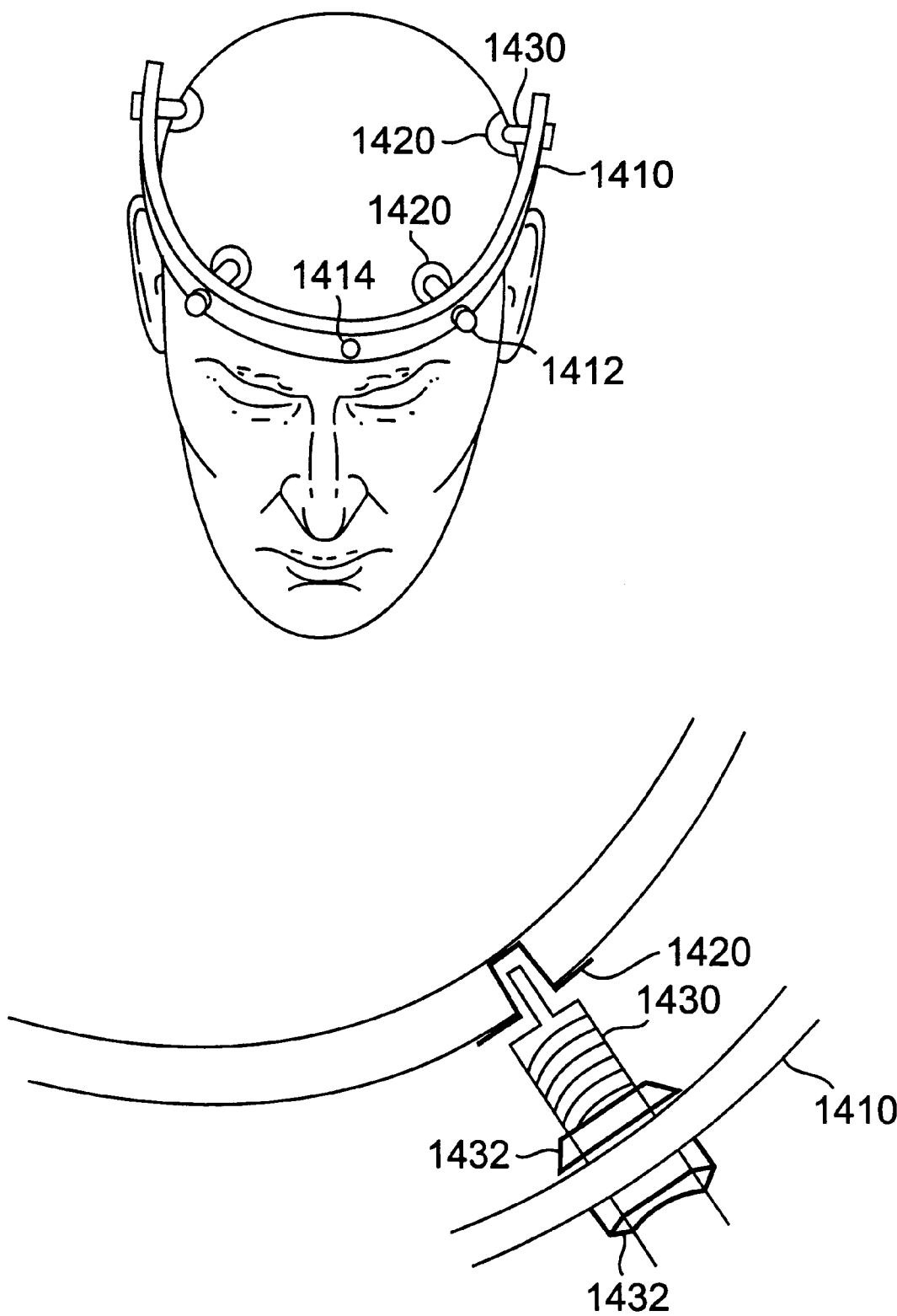


FIG. 20

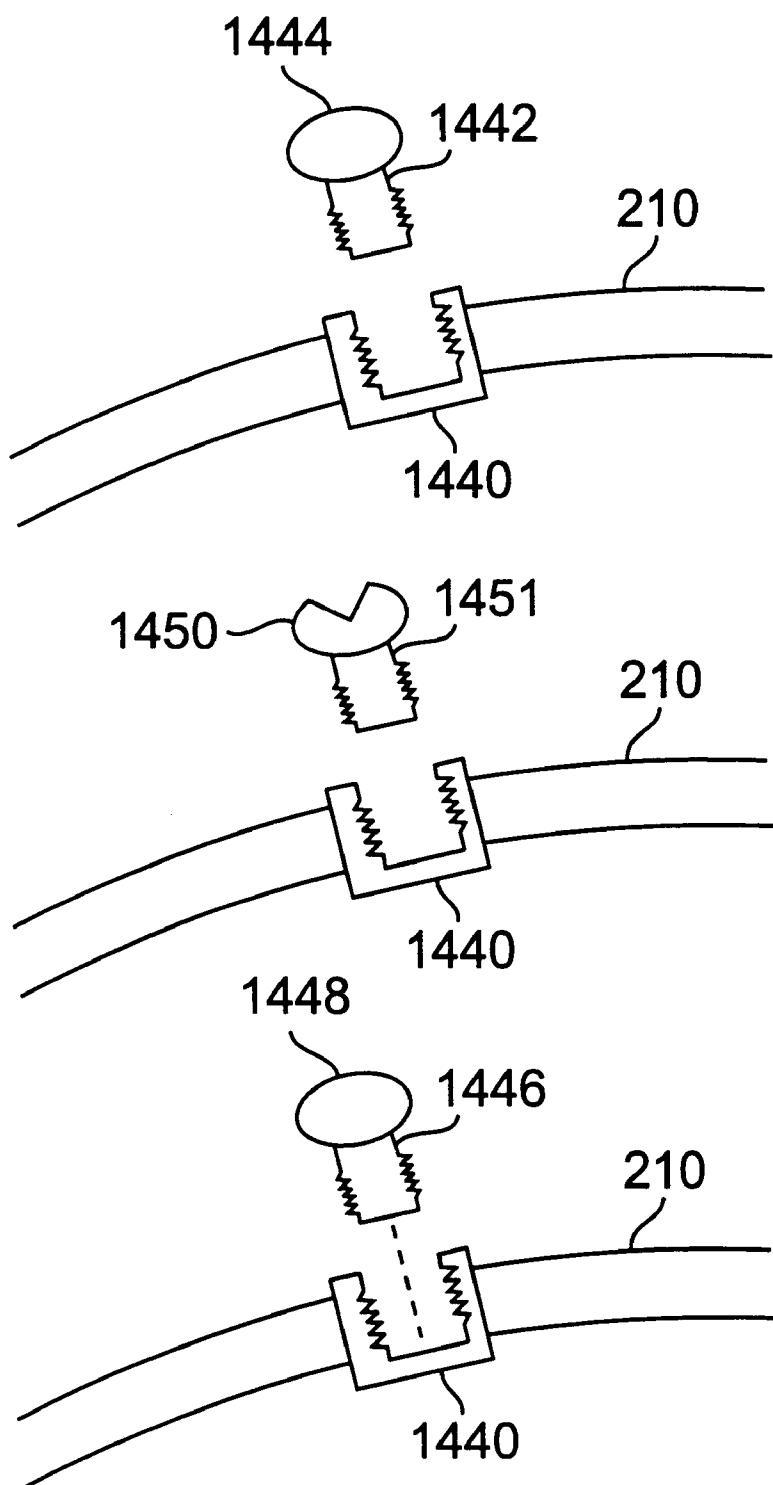


FIG. 21

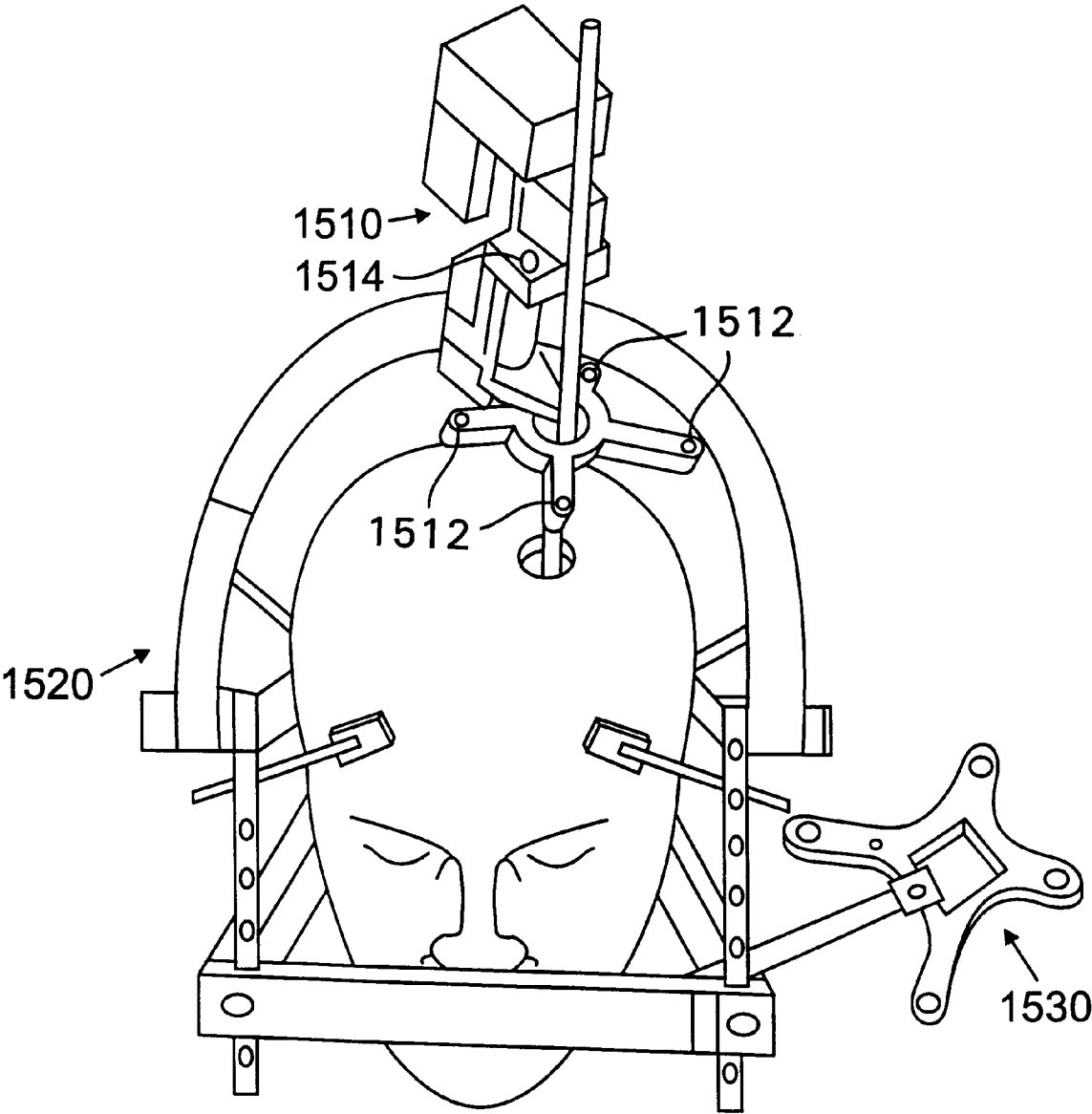


FIG. 22

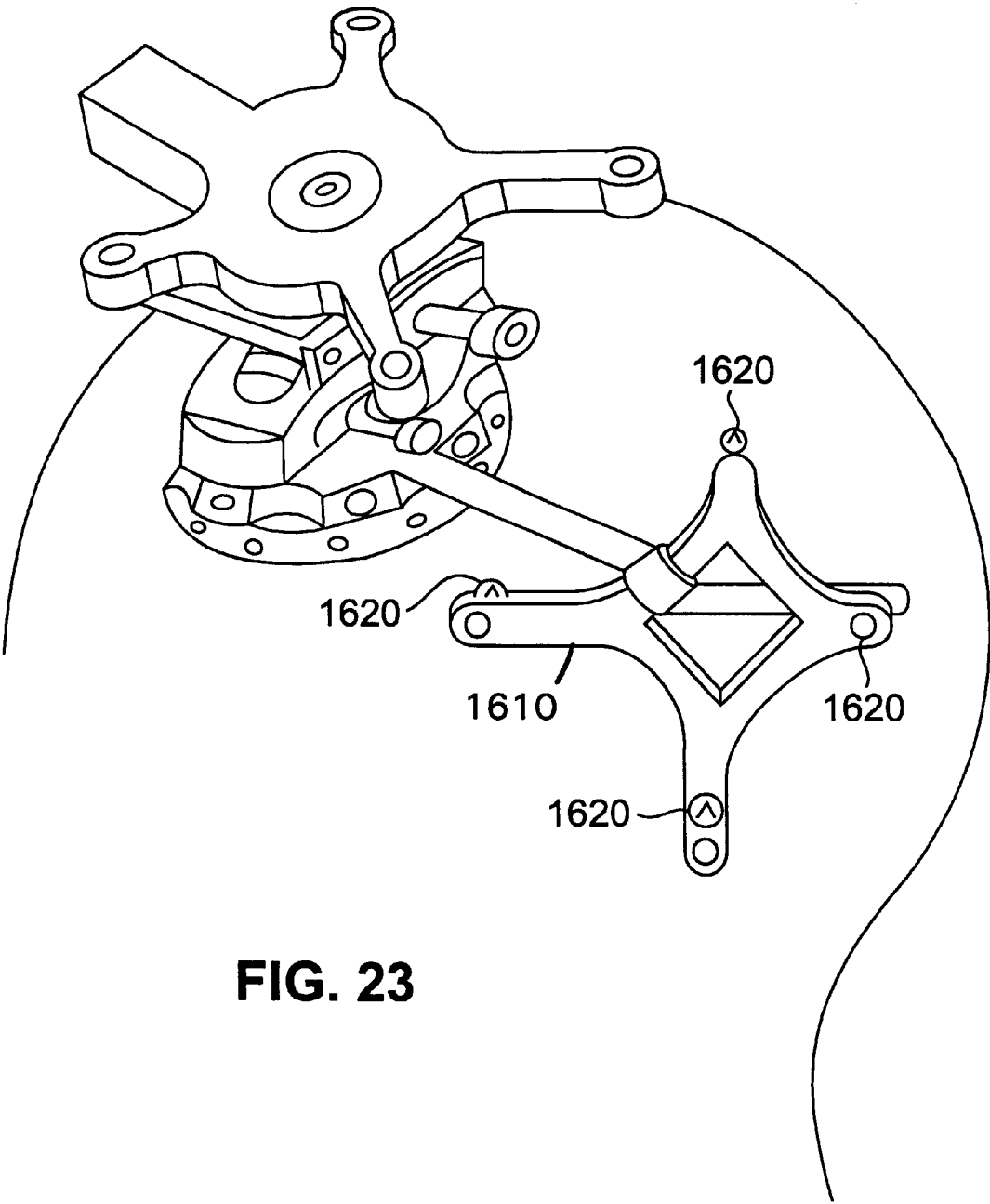


FIG. 23

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REMOVABLE FRAMES FOR STEREOTACTIC LOCALIZATION

BACKGROUND

This invention relates to removable frames for stereotactic localization.

Stereotactic localization is a method for locating a target within a three-dimensional object. This method is used in the medical arts and sciences to locate a target in the human body, in particular in the brain or spine, for medical and surgical treatment. Stereotactic surgery has a history dating back to the turn of the century, when the Horsely-Clark Apparatus was described as a mechanical frame system in which an animal was immobilized. This frame system permitted reproducible targeting within the animal's brain for physiological experiments. This and similar technology found application in 1948 in the work of Wycis and Spiegel. In their work, a frame was attached to a human skull. The frame permitted targeting of sites within the human brain for neurosurgical treatment. A detailed survey of the field of stereotactic surgery can be found in *Textbook of Stereotactic and Functional Neurosurgery*, P. L. Gildenberg and R. R. Tasker (eds.), McGraw-Hill, June 1997 (ISBN: 0070236046).

One approach to stereotactic surgery involves the following steps. Fiducial scanning markers are attached to the body in one of a variety of manners, including using an attachable frame or attaching the markers to the skin with an adhesive. A scan is then taken of a body, for example of the head, to produce a three-dimensional image of the body. Scanning can be done using a variety of techniques including CT, MRI, PET, and SPECT. Images of the fiducial scanning markers that are located around the body are then located in the three-dimensional image at fiducial image points. Points of interest, such as the location of a tumor, are located in the three-dimensional image with reference to these fiducial image points. The body and the image are registered by matching the locations of the scanning markers and the coordinates of the fiducial image points. In an approach to stereotactic brain surgery, a three-dimensional frame is screwed to the patient's skull prior to scanning the head. This frame serves as a mechanical reference mechanism that supports scanning fiducial markers at fiducial points around the body. The frame remains attached to the patient's skull from before scanning until after surgery is complete. Prior to surgery, a mechanical guide assembly is attached to the frame. The relative location in the image of the point of interest with respect to the fiducial image points is determined, and this relationship is used to adjust the mechanical guide assembly with respect to the fiducial points on the frame. Using the adjusted mechanical guide assembly, a surgical instrument is then guided to a location in the body that corresponds to the point of interest in the image.

In another form of stereotactic surgery, known generally as "image-guided" stereotactic surgery, rather than relying on mechanical adjustment of a guide assembly, visual feedback is provided to a surgeon by displaying a composite image formed from the scanned three-dimensional image and a synthesized image of a hand-held surgical instrument. The surgeon guides the hand-held instrument into the body using the visual feedback. In this form of surgery, a frame is attached to the patient and a scan is taken as described above. After scanning, the head and frame are secured in a fixed position, for example, fixed to an operating table. In order to display the image of the surgical instrument in a

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proper relationship to the scanned image, the position and orientation of the instrument is sensed using a localization apparatus that remains in a fixed position relative to the body. The localization apparatus can be coupled to the surgical instrument using an articulated mechanical arm on which the surgical instrument is attached. Sensors in the joints of the arm provide signals that are used to determine the location and orientation of the instrument relative to a fixed base of the mechanical arm. Some more recent systems do not use mechanical coupling between the surgical instrument and the localization apparatus and instead rely on remote sensing of small localized energy emitters (e.g., sources or transducers of energy) fixed to the instrument. For example, a camera array is used to locate light-emitting diodes (LEDs) that are attached to the instrument. The locations of the LED images in the camera images are used to determine the three-dimensional physical locations of the LEDs relative to the camera array. The locations of multiple LEDs attached to the instrument are then used to determine the location and orientation of the instrument. Another example of remote sensing uses sound generators and a microphone array and relies on the relative time of arrival of acoustical signals to determine the three-dimensional locations of the sound generators.

Before a synthesized image of the instrument can be combined with the scanned image in a proper relationship, some form of registration is required. For example, the tip of the surgical instrument can be placed at each of several fiducial markers for which corresponding images have been located in the three-dimensional scanned image. Registration of the synthesized image of the instrument and the scanned image can thereby be established.

In a variant of image-guided stereotactic surgery, generally known as "dynamic referencing," the head and frame are secured in a fixed position, as in the image-guided approach. However, unlike other image-guided techniques, the sensors (e.g., cameras) of the localization apparatus are not at a fixed location. In order to compensate for the motion of the sensors, energy emitters are fixed to the frame as well as to the instrument. At any point in time, the location and orientation of the frame relative to the sensors as well as the location and orientation of the instrument relative to the sensors are both determined, and the differences in their locations and orientations are used to compute the location and orientation of the instrument relative to the frame. This computed location of the instrument is then used to display the synthesized image of the surgical instrument in an appropriate relationship to the scanned image.

Still another approach to stereotactic surgery, generally known as "frameless image-guided" stereotactic surgery, does not rely on attaching a frame to the body before scanning. Instead, adhesive fiducial scanning markers are applied to the scalp, or small screws are inserted into the skull, and the patient is scanned as in the techniques described above. During surgery, the patient is immobilized and locked in place using a head clamp or a frame. The image-guided stereotactic approach described above is then followed, including the registration procedure described above to establish the locations of the fiducial scanning markers relative to the instrument.

In image-guided techniques, a surgeon can rely on a variety of views of a three dimensional scanned image. These views can include a three-dimensional surface view with an adjustable point of view (e.g., a perspective view with surface shading). In addition, planar (i.e., two-dimensional) views of the image can be displayed. In particular, three two-dimension "slices" through orthogonal

planes of the image are typically displayed, with the orientations of the planes being sagittal (dividing a head into a left and a right part), coronal (dividing a head into a front and a back part), and axial (dividing a head into an upper and lower part). As the orientations of the planes are predetermined, the particular planes that are displayed can be determined by the point of intersection of the three planes. A point, such as the tip of a probe, can be displayed in a three-dimensional surface view as a point in an appropriate geometric relationship. The point can be displayed in a planer view by orthogonally projecting the point onto the associated plane. A line can be displayed in a planar view as an orthogonal projection onto the associated plane, or as the point of intersection of the line and the associated plane. Note that if a first point, such as a surgical entry point is used to determine which planes are displayed, a second point, such as a surgical target point, does not in general fall in any of the displayed planes.

Planar views of a three-dimensional scan can also use alternative orientations than the standard sagittal, coronal, and axial orientations described above, allowing two points to lie in two orthogonal planes, and one of the two points to additionally lie in a third orthogonal plane. In particular, a “navigational” view can be determined according to two points in an image, such as an entry point at the surface of a body and a target point within the body. The line joining the entry point and the target point is chosen as the intersection of two orthogonal planes, navigation planes 1 and 2. The orientation of navigational planes 1 and 2 is arbitrary (that is, the two planes can be rotated together around their intersecting line). A third plane, orthogonal to navigation planes 1 and 2, provides a “bird’s eye” view looking from the entry point to the target point. This bird’s eye plane is typically chosen to pass through the target point. (Such a navigational view is shown in FIG. 14a). Using a navigational view, the orientation of a surgical instrument is typically shown as a line projected orthogonally onto the two navigational planes, and as the point of intersection of the line and the bird’s eye plane. Manipulating an instrument using such a navigational view for feedback requires considerable practice and is not intuitive for many people.

Image-guided frameless stereotaxy has also been applied to spine surgery. A reference frame is attached to an exposed spinous process during open spine surgery, and a probe is used to register the patient’s spine with scanned image of the spine. Anatomical landmarks are used as fiducial points which are located in the scanned image. Visual feedback is provided to manually guide placement of instruments, such as insertion of pedicle screws into the spinal structures.

SUMMARY

In one aspect, in general, the invention is a marking and tracking apparatus for stereotactic surgery on a body. The apparatus includes a rigid scanning frame. The scanning frame includes a set of scanning markers for making corresponding images in a scanned image of the body, and multiple mounting points, such that when the scanning frame is attached to the body, each of the mounting points mates with a corresponding one of multiples anchors, such as threaded inserts, embedded in the body. The apparatus can also include a rigid tracking frame. The tracking frame includes a set of tracking markers for tracking a position of the frame using a remote sensing device, and multiple mounting points, such that when the tracking frame is attached to the body, each of the mounting points mates with a corresponding one of the anchors embedded in the body.

The invention can include one or more of the following features:

The number of scanning markers is greater than the number of mounting points.

The number of tracking markers is greater than the number of mounting points.

Each of the anchors has a recess and the scanning frame and the tracking frame are attached to the body using posts that mate with the recesses.

The tracking markers are light emitting diodes and the remote sensing device includes an array of cameras.

The tracking frame includes a set of position indicators in the same geometric relationship to the mounting points on the tracking frame as the geometric relationship between the scanning markers and the mounting points on the scanning frame.

In another aspect, in general, the invention is a method for tracking a surgical instrument in relation to a body. The method include embedding a set of anchors in the body, and then attaching to the body a rigid scanning frame which includes a plurality of scanning markers, including attaching the scanning frame to the anchors at a corresponding set of mounting points on the scanning frame. The method further includes scanning the body to produce the three-dimensional image of the body which includes images of the scanning markers, and then removing the scanning frame. Then method then include attaching to the body a rigid tracking frame which includes a set of tracking markers, including attaching the tracking frame to the anchors at a corresponding set of mounting points on the tracking frame. The method also includes tracking locations of the tracking markers using a remote sensing device and determining locations of the scanning markers on the previously attached scanning frame in relation to the tracked locations of the tracking markers. The method further includes tracking a location of the surgical instrument using the remote sensing device and determining a location of the surgical instrument in relation to the locations of the scanning markers on the previously attached scanning frame.

In yet another aspect, in general, the invention is a method for reattaching a surgical frame to a body including embedding multiple anchors in the body and attaching the frame to the anchors at corresponding mounting points on the frame. The method then includes removing the frame from the body and subsequently reattaching the frame to the anchors at the corresponding mounting points.

An advantage of the invention is that surgical frames can be precisely attached to the body using embedded anchors. In particular, a scanning frame can be attached for scanning and then removed. Subsequently, a tracking frame can be attached such that the locations of scanning points on the previously attached scanning frame can be precisely determined in relation to points on the tracking frame. For example, the tracking frame can have visible markings on it which are in the same locations relative to the anchors and the scanning markers on a previously attached scanning frame. By allowing removal and subsequent precise attachment of frames, a patient is not required to have a frame continuously attached from prior to scanning through subsequent stereotactic surgery.

Other features and advantages of the invention will be apparent from the following description, and from the claims.

DESCRIPTION OF THE DRAWING

FIG. 1 is a flowchart of a stereotactic brain surgery procedure;

FIG. 2 is a head with threaded inserts implanted including a cross-sectional view of the skull and a threaded insert;

FIG. 3 is a head with a scanning MIRRF attached including a detailed exploded view of the attachment of the MIRRF to the implanted threaded inserts;

FIG. 4 illustrates scanning of a head on which a scanning MIRRF is attached;

FIG. 5 is a head with a tracking MIRRF attached and a cranial probe being tracked using a camera array;

FIG. 6 is a dataflow diagram for computation of a composite image including a synthesized image of a probe;

FIG. 7 illustrates locating a planned entry point using the tracked cranial probe and a computer display;

FIG. 8 is a display of a virtual burr hole and accessible cone of orientations;

FIG. 9 is a head with a tracking MIRRF and a guidance fixture attached being tracked using a camera array;

FIG. 10 is a view of a base platter and an adjustable base of a guidance fixture;

FIG. 11 is an exploded view of the adjustable base of a guidance fixture;

FIG. 12 is a dataflow diagram for computation of a composite image including a synthesized image of a surgical instrument;

FIG. 13 is a detailed flowchart of trajectory replanning and fixture alignment;

FIGS. 14a-c illustrate a navigational view display and corresponding planar segments through a body;

FIGS. 15a-f illustrate a "field of view" display and corresponding conical section through a body;

FIG. 16 is a guidance fixture including an adjustable base and an instrument drive attached to a base platter;

FIG. 17 is a retractor in a guidance fixture;

FIG. 18 is a calibration jig;

FIG. 19 is a phantom jig and a guidance fixture and a tracking MIRRF attached to the jig;

FIG. 20 is an arc shaped MIRRF attached to a head including a view of a threaded insert and mounting bolt;

FIG. 21 is a scanning marker and a tracking marker attached to a threaded insert;

FIG. 22 is a guidance fixture and a tracking MIRRF attached to a conventional stereotactic frame; and

FIG. 23 is a tracking MIRRF attached directly to a guidance fixture.

DESCRIPTION

Referring to FIG. 1, an aspect of the invention relates to stereotactic brain surgery. This approach to brain surgery involves a series of steps, shown in FIG. 1, from start 100 prior to scanning through finish 199 after the surgical phase of a procedure is completed. There are generally two phases to the approach. The first phase involves creating a three-dimensional image of the head (steps 105, 110, 115, 120), planning a surgical trajectory based on the image (step 125), and validating the guidance fixture (step 130) that will be used during the surgical procedure. The second phase involves the remaining steps (steps 135 through 195) that are used to carry out the actual surgical procedure. The steps of the first phase can be carried out quite some time before those of the second phase. For example, creating the three-dimensional image of the head can be done on one day, and the steps used to carry out the actual surgery can be done on a subsequent day. Also, the steps of the second phase may be

repeated, for example on several different days, illustrated by transition 192 between steps 195 and 135.

One to three days prior to surgery, the patient is seen in a post anesthesia care unit (PACU) or other suitable location. Referring to FIG. 1, the first step of the procedure is to attach anchors to which scanning, registration, and tracking markers will be subsequently attached (step 105). Referring to FIG. 2, the anchors include two threaded inserts 220 that are surgically implanted into the patient's skull 210 using a template (described below). The template precisely determines the separation and parallel orientation of inserts 220.

Referring to FIG. 3, a rigid cross-shaped device, a scanning "miniature removable reference frame" (scanning MIRRF) 310, is next attached to threaded inserts 220 using screws 320 (FIG. 1, step 110). A retention plate 330 is used to aid precise reattachment of scanning MIRRF 310 to the skull. Retention plate 330 is also used as the template during insertion of threaded inserts 220. Scanning MIRRF 310 includes four fiducial scanning markers 340 that will be visible in the scanned image. Scanning MIRRF 310 is made from a material that is chosen to interfere as little as possible with the type of scan that will be performed. For example, for MRI and CT scans, the chosen material can be polycarbonate, which results in scanning MIRRF 310 being almost invisible in the scanned image. Fiducial scanning markers 340 are mounted in spherical cavities in scanning MIRRF 310. The design of the cavities is such that the "press-in" marker inserts can be removed for cleaning. The star-shaped design of scanning MIRRF 310 is such that, when attached, the elongated part of the star extends behind or in front of the ear so that mounting screws 320 are located toward the top of the skull where soft tissue thickness is minimal and skull thickness is maximal. This minimal tissue thickness allows threaded inserts 220 to be implanted easily under local anesthetic by making a small incision. As an alternative to attaching a single MIRRF as shown in FIG. 3, multiple MIRRFs can be attached in a similar manner to increase the number or separation of the scanning markers.

Referring to FIG. 4, MRI or CT scanner 400 is used to obtain a three-dimensional digitized image 410 of the head, for example, as a series of two-dimensional "slices" (step 115 in FIG. 1). In addition, a model or map of the surface of the skull can be made allowing, for instance, subsequent three-dimensional surface display of the skull. The fiducial scanning markers 340 produce fiducial images 420 at in image 410. Fiducial coordinates 421 of fiducial images 420 in the coordinate system of image 410 are determined, for example, by manually positioning a cursor at fiducial images 420 on a computer display. Image 410, along with the fiducial coordinates 421, are stored on a computer readable storage medium 430 for use during the subsequent surgical phase of the approach. Typically the image is stored as a series of two-dimensional images, each corresponding to a horizontal "slice" of the head.

After scanning, scanning MIRRF 310 is removed (FIG. 1, step 120), and threaded inserts 220 are left in place. Antibiotic ointment can be applied and the patient is either discharged or sent to the operating room.

Also after scanning, a surgeon determines the location of a target point within the brain and an entry point through the skull (FIG. 1, step 125). A planned surgical trajectory is then determined as the line joining the entry point and the target point. The surgeon plans the trajectory using a computer display of image 410 which provides, for example, a three-dimensional surface view, and sagittal, coronal, and axial planar views. This allows the surgeon, for example, to plan

a trajectory that avoids critical structures in the brain. The target and entry points, and the trajectory are stored along with the image on storage medium 430.

Other than an optional fixture validation (FIG. 1, step 130), all the preoperative steps are complete at this point.

Referring to FIG. 5, the surgical phase of the procedure begins by attaching a tracking MIRRF 510 to threaded inserts 220 (not shown) that remained implanted in the patient's skull after scanning MIRRF 310 was previously removed. Tracking MIRRF 510 has a very similar structure to scanning MIRRF 310. Tracking MIRRF 510 includes fiducial divots 540 at the centers of locations corresponding to fiducial markers 340 (shown in FIGS. 3 and 4). Four tracking LEDs 550 are also attached to tracking MIRRF 510. Since tracking MIRRF 510 is rigid, the geometric relationship between tracking LEDs 550 and fiducial divots 540 is fixed and can be determined beforehand and verified in a subsequent verification step, or can be unknown and determined in a subsequent registration step. Preferably, tracking MIRRF 510 is made of a material that is lightweight and can be autoclaved, such as Radel.

After attaching tracking MIRRF 510 to the patient's skull, the patient can be comfortably placed in an awake, possibly lightly sedated, state in an operating room chair, which is similar to a dental chair. The patient is allowed to recline in an essentially unrestrained manner in the operating room chair in a semi-sitting position. Alternatively, at the surgeon's prerogative and if appropriate, general anesthesia can be administered to the patient.

Referring still to FIG. 5, a camera array 560 provides time-varying digitized images 586 to a localization application 588 executing on a computer workstation 580. The patient can be free to move relative to camera array 560 and relative to the operating room chair, and camera array 560 can be free to move relative to the patient and relative to the operating room chair. Camera array 560 includes three CCD cameras 562 positioned in a fixed configuration relative to one another. Alternatively, two cameras, which are sufficient for three dimensional localization, or more than three cameras, which may provide greater accuracy, can be used. Each camera 562 in camera array 560 produces one time-varying image. Each tracking LED 550 on tracking MIRRF 510 is powered and emits infra-red illumination which is seen as a bright point in each of time-varying digitized images 586. Based on the relative coordinates of the bright points in images 586 from each camera 562 of camera array 560 localization application 588 computes the position (i.e., the coordinates) of tracking LEDs 550 in the coordinate system of camera array 560. Using the positions of multiple tracking LEDs 550, the location and orientation of tracking MIRRF 510 can be computed by localization application 588. Tracking of MIRRF coordinates 510 is illustrated schematically by line 564.

A cranial probe 570, including three probe LEDs 572 attached along its length, is also tracked using camera array 560 and localization application 588. Based on the coordinates of the images of probe LEDs 572 in images 586 and probe geometry 584, localization application 588 computes the position and orientation of probe 570 in the coordinate system of camera array 560.

Using cranial probe 570, the surgeon then carries out a registration step (FIG. 1, step 140). In this registration step, the surgeon first locates the fiducial points in the image. Then he touches the tip of probe 570 to each of fiducial divots 540 in tracking MIRRF 510 in turn, indicating to localization application 588 when he is touching each of the

divots. Localization application 588 then computes a three-dimensional conformal registration (map) between image 410 and the coordinate system of tracking MIRRF 510.

Note that if the geometric relationship of tracking LEDs 550 and fiducial divots 540 is known to localization application 588, for example using a previously calibrated MIRRF, the coordinates of the fiducial divots can be computed from the coordinates of the tracking LEDs, which in turn can be computed from the locations of the fiducial images in the camera images. The step of touching the divots can be omitted in this case, or used to verify the computed coordinates of fiducial divots.

Having computed the conformal mapping, localization application 588 continuously combines image 410 and a synthesized image of probe 570 to form a composite image 599 that combines the scanned image with the synthesized image of the probe. Composite image 599 is shown on a computer display 610 which includes a three-dimensional surface display.

Referring to FIG. 6, the registration and image composition functions performed by localization application 588 involves a series of data processing stages. As shown in FIG. 5, time-varying digitized images 586 are provided to localization application 588 from camera array 560. Referring to FIG. 6, time-varying digitized images 586 are input to MIRRF tracking 591, a processing stage of localization application 588, which tracks tracking LEDs 550 on tracking MIRRF 510 and produces "MIRRF/cam" 593, an orientation and location of tracking MIRRF 510 in the coordinate system of camera array 560. At the same time, probe tracking 590 tracks probe 570 and produces "probe/cam" 592, an orientation and location of probe 570 in the coordinate system of camera array 560. Probe tracking 590 makes use of probe geometry 584 which specifies the geometric relationship between the tip of the probe 570 and probe LEDs 572. The next stage of localization application 588, relative positioning 594 inputs MIRRF/cam 593 and probe/cam 592 and produces "probe/MIRRF" 595, the position and orientation of probe 570 in the coordinate system of tracking MIRRF 510. When the surgeon touches fiducial divots 540, registration 581 takes the location information from probe/MIRRF 595 and records it in "fids/MIRRF" 582, the coordinates of fiducial divots 540 in the coordinate system of tracking MIRRF 510. Fiducial coordinates 421, the coordinates of fiducial images 420 in the coordinate system of image 410, are provided to localization application 588, along with image 410, from storage medium 430. Mapping 587 includes matching of corresponding coordinates in fids/MIRRF 582 and fiducial coordinates 421 and forming a conformal map 589 between the coordinate system of image 410 and the coordinate system of tracking MIRRF 510. Conformal map 589 includes the quantities required to transform any three-dimensional coordinate in the coordinate system of tracking MIRRF 510 into a three-dimensional coordinate in the coordinate system of image 410. These quantities correspond, in general, to a rotation, scaling, and translation of points in the coordinate system of tracking MIRRF 510 to determine the corresponding points in the coordinate system of image 410.

Referring still to FIG. 6, the next stage of localization application 588, probe mapping 596, takes the continually updated probe coordinates, probe/MIRRF 595, and conformal map 589, and computes probe/image 597, the coordinates of probe 570 in the coordinate system of image 410. Then, image composition 598 combines image 410 and a synthesized image of probe 570 to form composite image 599.

Composite image 599 typically includes a three-dimensional surface view and three orthogonal planar views. The orthogonal planar views can correspond to the three standard orientations, sagittal, coronal, and axial planes, for instance passing through the planned target point. More typically, three planar views of a navigational view that is determined by the planned entry and target points are included in composite image 599. The tip of the probe is displayed as an orthogonal projection onto the planes of the planar views, and as a point in an appropriate geometric relationship in the three-dimensional surface view. The orientation of the probe can be displayed using a line passing through the tip of the probe and displayed as a orthogonal projection onto navigational planes 1 and 2 of the navigational view, and as a point of intersection on the bird's eye view of the navigational view.

If the geometric relationships of the fiducial points, fids/MIRRF 582, the coordinates of fiducial divots 540 does not match the geometric relationships of fiducial coordinates 421, then an error in placing probe 570 during the registration procedure may have occurred. If such an error is detected, conformal mapping 589 is not computed, a warning is provided to the surgeon, and the surgeon must perform the registration procedure again. Furthermore, if the geometric relationships between fiducial divots 540 is known through prior measurement or calibration, registration errors and errors locating fiducial points 420 in image 410 can also be detected.

Referring to FIG. 7, a cranial probe 570 is used to determine an actual entry point. A computer display 610 shows composite image 599, which includes a three-dimensional surface view and three planar views of a navigational view determined by the planned entry and target points.

Referring to FIG. 8, a virtual burr hole 640 is displayed in the planar views of navigational view at the probe location 642 of cranial probe 570. In addition, the range of adjustable orientations of a guidance fixture that would be attached at probe location 642 is displayed as a cone 644, and the extent of effects of x-y adjustment of the guidance fixture is displayed as a second cone 646. Display of cones 644 and 646 allows the surgeon to verify that planned target point 650 is accessible in the range of adjustments of a guidance fixture attached at probe location 642.

When the surgeon has located an entry point 620 on the skull, he marks the entry point as the desired center point of attachment of a guidance fixture that will be used during the surgical phase of the procedure.

The patient then has a small area of the head shaved and draped off. A 2 to 4 cm linear incision is made over entry point 620 after local anesthesia is administered. The location of entry point 620 is then reconfirmed using cranial probe 570 after the incision is made. An approximately 1 cm burr hole (not shown in FIG. 7) is then drilled through the skull at entry point 620 (FIG. 1, step 150). The surgeon opens the dura under the burr hole and visually inspects the area to determine that no critical structures, such as a blood vessel, are located directly under the burr hole. If the location of the burr hole is found to be unacceptable, a new entry point can be planned and return to the step of locating the entry point (FIG. 1, step 145).

Referring to FIG. 9, having drilled the burr hole, the surgeon next attaches a guidance fixture 710 to the skull (FIG. 1, step 155). (Note that an optional instrument drive can also be included in the guidance fixture but is not shown in FIG. 9.) As is described more fully below, guidance fixture

710 includes a base platter 720 on which platter LEDs 730 are attached. Base platter 720 is attached to an adjustable base 715, which is in turn attached to the skull. The orientation of a line normal to base platter 720 is adjustable within a cone forming a solid angle of approximately 45 degrees. After attaching guidance fixture 710 the surgeon adjusts the orientation of base platter 720 (FIG. 1, step 170; note that optional steps 160 and 165 are described below). A surgical instrument 740, including an instrument LED 742 fixed relative to the instrument, passes through guidance fixture 710. Surgical instrument 740 is constrained to follow a fixed trajectory perpendicular to and through a central opening through adjusted base platter 720. Workstation 580 tracks the location and orientation of base platter 720, and the displacement of surgical instrument 740, indicated schematically by lines 564 and 750 respectively, and computes the position of surgical instrument 740 in the coordinate system of image 410. Workstation 580 continually displays on display 610 a composite image 750 including a navigational view of image 410 showing the position and orientation of surgical instrument 740. The surgeon uses the visual feedback on display 610 to position surgical instrument 740 along the constrained trajectory. Note that during this time, the patient is not necessarily immobilized. Both the patient and camera array 560 can move and, as long as platter LEDs 730 and instrument LED 742 are visible to camera array 560 at an appropriate distance and orientation, workstation 580 can maintain a continuously updated display.

Referring to FIG. 10, guidance fixture 710 includes base platter 720 and adjustable base 715. In use, base platter 720 is attached to an entry column 850 (through an x-y positioning table 1150, described fully below) which is held in adjustable base 715. The orientation of entry column 850 can be adjusted relative to skull 210 using separate rotation and pivoting motions, as described below. Referring also to the exploded view of adjustable base 715 shown in FIG. 11, guidance base 715 includes a mounting base 820, which is rigidly attached to the skull during an operation using screws through mounting holes 822. Mounting holes 822 pass through mounting tabs 723 as well as through the inside of the mounting base 820. Mounting tabs 823 are pliable to allow them to conform to the skull. As mounting base 820 may be distorted in being mounted to the skull, it can be designed to be disposable. Mounting base 820 has a cylindrical opening which accepts a rotating collar 830. A rotation locking screw 824 in mounting base 820, when tightened, locks rotating collar 830 in place and prevents its movement within the mounting base. Entry column 850 is held within rotating collar 830 by a pivoting collar 840. Pivoting collar 840 slides in an arc-shaped pivoting guide 841 within rotating collar 830. When rotated, a pivoting locking knob 846 prevents pivoting collar 840 from sliding by drawing a collar clamp 842 against pivoting collar 840 using a threaded rod 920. When rotated, a pivoting adjustment knob 844 slides pivoting collar 840 along pivoting guide 841.

Referring again to FIG. 11, mounting base 820 includes mounting holes 822 drilled through mounting tabs 723 (one tab is not visible on the side opposite the visible one), as well as through the inside of mounting base 820. Mounting base 820 includes a threaded hole 922 within which rotation locking screw 824 turns. Rotation locking screw 824 mates with a recessed channel 923 in rotating collar 830, thereby preventing rotation of rotating collar 830 and also preventing rotating collar 830 from lifting off mounting base 820.

Entry column 850 includes a cylindrical portion 913 and a spherical portion 914 at one end. Spherical portion 914

mates with a spherical socket **916** in the bottom of rotating collar **830**. When mated, entry column **850** can pivot within rotating collar **830**. Entry column **850** also has opposing groves **910** which mate with protrusions **912** on the inside of the circular opening in pivoting collar **840**. Entry column **850** passes through the circular opening, and protrusions **912** mate with groves **910**. When assembled, the mated groves and protrusions hold the spherical portion **914** of entry column **850** against spherical socket **916** in the bottom of rotating collar **830**.

The position of pivoting collar **840** within pivoting guide **841** is adjusted by turning pivoting adjustment knob **844** and tightened in place by rotating pivoting tightening knob **846**. Pivoting adjustment knob **844** attaches to a pivoting adjustment rod **930** which passes through collar clamp **842** and the main portion of pivoting collar **840** to a rack and pinion mechanism. A pinion **931** is attached to the end pivoting adjustment rod **930**. Pinion **931** mates with an arc-shaped rack **932** which attaches to rotating collar **830** using three screws **934**. Rotation of pivoting adjustment knob **844** rotates pivoting adjustment rod **930** and pinion **931**, which then slides pivoting collar **840** in pivoting guide **841**. Rotating pivoting locking knob **846** locks pivoting collar **840** rigidly to rotating collar **830**. Tightening both rotation locking screw **824** and pivoting locking knob **846** fixes the orientation of entry column **850** relative to mounting base **820**.

Referring to FIG. **10**, the procedure for attaching and adjusting guidance fixture **710** (FIG. **1**, steps **155** through **170**) is carried out as follows. Mounting base **820** is attached in a temporary fashion over burr hole **625**. While attaching the base, mounting tabs **723** are conformed to the shape of the skull **210** and secured to the skull an orientation generally directed towards the target using three or more titanium bone screws **724** passing through mounting holes **822** through mounting tabs **723** and through the interior of the mounting base.

After mounting base **820** is attached to skull **210**, the remainder of guidance base **715** is attached to mounting base **820**. In particular, rotating collar **830**, with entry column **850** already attached, and adjusted to be centered (oriented along the central axis of guidance base **715**) is inserted in mounting base **820** and rotation locking screw **824** is tightened to mate with recessed channel **923**.

After guidance base **715** is attached to skull **210**, the remainder of guidance fixture **710** is attached to guidance base **715**. In FIG. **10**, the drive assembly, which is already attached to base platter **720** at the time base platter **720** is attached to guidance base **715** is not shown. Base platter **720** is attached to entry column **850** via an x-y positioning table **1150** (described below). During the alignment phase in which the orientation of guidance base **715** is adjusted, x-y positioning table **1150** remains centered.

During a surgical procedure, surgical instrument **740** is passed through a central opening **721** of base platter **720** and through entry column **850** into the brain. During the alignment phase in which x-y table **1150** is centered, a line along the trajectory surgical instrument **740** would follow passes along the central axis of entry column **850**. Adjusting the orientation of guidance base **715** adjusts this trajectory. In all orientations, the trajectory passes through a single point on the central axis of guidance base **715** near the surface of the skull. If the guidance base is exactly mounted over the planned entry point, this single point is the planned entry point. More typically, the point is slightly displaced from the planned entry point due to mounting inaccuracies.

Referring again to FIG. **9**, platter LEDs **730** on base platter **720** are sensed by camera array **560**, and the location and orientation of base platter **720** in the coordinate system of image **410** is computed by localization application **588** executing on computer workstation **580**. Localization application **588** computes the location and orientation of base platter **720** using the known geometry of the base platter relative to platter LEDs **730**.

Referring to FIG. **12**, localization application **588** computes composite image **750** (FIG. **9**) in a series of data transformations. Time-varying digitized images **586** are passed to MIRRf tracking **591** as well as platter tracking **7010** and instrument tracking **7012**. MIRRf tracking **591** produces "MIRRf/cam" **592**, the position and orientation of tracking MIRRf **510** in the coordinate system of camera array **560**. Platter tracking **7010** produces "platter/cam" **7020**, the position and orientation of base platter **720**. The instrument trajectory is at a known location and orientation relative to platter LEDs **730** on base platter **720**, therefore the location and orientation of the instrument trajectory in the coordinate system of camera array **560** is also known. Instrument tracking **7012** produces instrument/cam **7022**, the location of instrument LED **742** in the coordinate system of camera array **560**. Platter localization **7030** uses conformal map **589**, MIRRf/cam **593**, and platter/cam **7020** to compute platter/image **7040**, the location and orientation of base platter **720** in the coordinate system of image **410**. Note that once guidance fixture **710** is attached and aligned, then base platter **720** no longer moves relative to the skull (other than due to adjustment of x-y table **1150**) and therefore, platter/image **7040** can be fixed rather than continuously recomputed. Instrument depth measurement **7032** combines platter/cam **7020** and instrument/cam **7022** to compute instrument/platter **7042**, the depth of penetration of the surgical instrument relative to the plane of base platter **720**. Instrument depth measurement **7032** makes use of the known displacement of the tip of the instrument from instrument LED **742**. Instrument localization **7050** takes platter/image **7040** and instrument/platter **7042** and computes instrument/image **7060**, the location and orientation of the surgical instrument in the coordinate system of image **410**. Finally, image composition **7070** combines image **410** with a synthesized image of the surgical instrument to generate a composite image **750**.

Referring to FIG. **13**, before aligning guidance fixture **710**, the surgical trajectory is optionally replanned to go through the center of the actual mounted position of the guidance fixture, rather than the planned entry point (FIG. **1**, step **165**).

The surgeon aligns guidance fixture **710** using visual feedback. Referring to FIGS. **14a-c**, a navigational view indicating the trajectory of the surgical instrument is used. Referring to FIG. **14a**, navigational planes **1020** and **1022** correspond to navigational planar views **1030** and **1032** respectively. Navigational planes **1020** and **1022** are orthogonal and their intersection forms a line passing through an entry point **1010** and a target point **1012**. Bird's eye plane **1024**, the third plane of the navigational view, is orthogonal to planes **1020** and **1024** and passes through target point **1012**.

Referring to FIGS. **14b-c**, navigational planes **1020** and **1024** are shown schematically, along with a line **1040** corresponding to the orientation of guidance fixture **710**. The goal of the alignment procedure is to make line **1040** coincident with the intersection of planes **1020** and **1022**. The alignment procedure is carried out in a series of two motions each of which is constrained to one degree of

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freedom. Initially, line 1040 is not generally coincident with either navigational plane. Prior to beginning the alignment procedure, the orientation of line 1040 is displayed as orthogonal projections, lines 1041 and 1042, on planes 1020 and 1022, respectively.

In the first alignment motion, rotating collar 830 is rotated within mounting base 820 (FIGS. 10 and 11). Referring to FIG. 14b, this rotation causes line 1040 to sweep out a portion of a cone, indicated diagrammatically by dashed arrow 1050. After rotation through an angle Φ_1 , orientation line 1040 is in the direction of line 1043, which is coincident with plane 1022. During the rotation, the orthogonal projection line 1041 of line 1040 in plane 1020 forms a smaller and smaller angle θ_1 with the desired orientation in plane 1020, while the angle θ_2 between the orthogonal projection line 1042 in plane 1022 and the desired orientation in plane 1022 increases, ultimately to Φ_2 when line 1040 is coincident with plane 1022.

Referring to FIG. 14c, the second alignment motion reduces the angle Φ_2 while maintaining the coincidence of the orientation line and plane 1022. This motion corresponds to sliding pivoting collar 840 within rotating collar 830 (FIGS. 8 and 9). Alignment is achieved when angle Φ_2 is zero, that is, the orientation line 1040 is coincident with the intersection of planes 1020 and 1022.

At this point, after tightening the locking knobs on guidance fixture 710, base platter 720 is firmly fixed to the skull, in an orientation and location that constrains a surgical instrument passing through it to pass along the replanned trajectory to the planned target point in the head.

In addition to, or as an alternative to, using a navigational view to provide visual feedback during the alignment procedure, a "field of view" display can be provided. Referring to FIGS. 15a-f, the field of view display uses a representation of a cross-section of a cone extending below the entry point. Referring to FIG. 15a, the central axis of a cone 1061 is coincident with the central axis of the mounting base of a guidance fixture mounted at an entry point 1010. That is, the central axis of the cone is generally perpendicular to the surface of the skull at the entry point. The angle of the cone corresponds to the range of possible alignments of a guidance fixture mounted at the entry point. In this embodiment, this is a 45 degree angle. The cross-section is normal to the central axis of the cone, and passes through a target point 1012. Referring to FIG. 15b, the corresponding display shows a circular section 1070 of the scanned image. The center 1011 and the target point 1012 are indicated. Also indicated are two orthogonal axes. An axis 1072 corresponds to the achievable orientations of the guidance fixture as its pivoting collar is moved in the rotating collar. Another axis 1074 is orthogonal to axis 1072. Motion of the rotating collar rotates the orientation of axes 1072 and 1074. These axes can be thought of as intersections of the navigational planes with the bird's eye plane of a navigational view, although here, the intersecting lines rotate with the rotation of the guidance fixture while in the navigational view, the navigation planes remain fixed as the guidance fixture is rotated. Referring to FIG. 15c, after an appropriate rotation, axis 1072 passes through target point 1012. FIG. 15d shows the display after this rotation. Motion of the pivoting collar is indicated by a line 1076, parallel to axis 1074. If the pivoting collar is centered, then line 1076 is aligned with axis 1074, as is shown in FIG. 15d. When the guidance fixture is aligned with the target point, line 1076 passes through target point 1064, as does axis 1072. FIG. 15f, corresponding to FIG. 15e, shows the display after alignment is achieved. This circular field of view display provides

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intuitive visual feedback to the surgeon who is aligning the guidance fixture. Furthermore, displacement of the x-y table can also be shown in such a field of view display, by indicating the intersection of the resulting instrument trajectory on the circular display.

Referring to FIG. 16, an instrument drive 1110 is attached to base platter 720 prior to attaching the combination of instrument drive 1110, base platter 720, and x-y table 1150 to guidance base 715. In FIG. 16, instrument drive 1110 is shown partially mounted onto a drive post 1120. Prior to attachment to guidance base 715, drive post 1120 is fully inserted into instrument drive 1110 so that instrument drive 1110 is in contact with base platter 720. Base platter 720 can be displaced relative to guidance base 715 in a plane orthogonal to entry column 850 using two perpendicular adjustment screws 1060, and 1062 turned by x-y table adjustment knobs 1061, and 1063. Note that prior to alignment (FIG. 1, step 170) the x-y table is adjusted so that central opening 721 in base platter 720 is centered over entry column 850.

Instrument drive 1110 includes a drive platform 1130 that moves within a drive mechanism 1125 along a threaded rod 1132. Threaded rod 1132 is oriented parallel to drive post 1120 and perpendicular to base platter 720. In this embodiment, rotation of threaded rod 1132, which causes displacement of drive platform 1130, is manual using a mechanism that is not shown. Alternative embodiments can use an electronic stepper motor or a manual hydraulic drive to rotate threaded rod 1132 and thereby displace drive platform 1130.

In operation, a surgical instrument, such as a micro-electrode, is passed into the brain through a guidance tube. After alignment of guidance fixture 710, the guidance tube is manually inserted into the brain through central opening 721 in base platter 720. The guidance tube is then secured in clamp 1135 that is fixed relative to drive mechanism 1125. The instrument is passed into the guidance tube and is secured in a clamp 1133, which is fixed relative to drive platform 1130.

Instrument LED 742 is attached to drive platform 1130. The displacement of the end of the surgical instrument from instrument LED 742 is known to localization application 588 which executes on workstation 580. By tracking the position of instrument LED 742, as well as platter LEDs 730, the position of the end of a surgical instrument on workstation 580 and displayed on display 610 (FIG. 9) to the surgeon. The surgeon then uses this visual feedback in adjusting the depth of the instrument.

Various types of surgical probes or instruments can be attached to drive mechanism 1110 shown in FIG. 16. One type of instrument is an electrode, such as a recording micro-electrode or a stimulating electrode or lesioning electrode. The electrode is introduced into a rigid insertion (guidance) tube that is attached to drive mechanism 1110. Another type of instrument is a hypothermia cold probe.

In cases of movement disorder or pain surgery, a chronically implanted stimulating electrode can be placed utilizing an insertion tube. The lead, being of a smaller diameter than the insertion tube, can be slipped through the insertion tube upon removal of the drive and guide assembly, to allow fixation of the chronically implanted electrode into the brain. The electrode is secured to the skull using a compression-fitting. A chronically implanted recording electrode can similarly be placed during epilepsy surgery to monitor abnormal activity within the deep brain utilizing similar techniques.

In cases of hydrocephalus or other situations where chronic drainage of intracranial cavities is necessary, a shunt tube, such as a ventricular shunt, can be applied through the insertion tube into the target such as the ventricles of the brain. The shunt tube will have a stylet and be slipped into the insertion tube.

The insertion tube structure and its retention ring will have varying diameters, depending on the diameters of the various objects that can be placed in the insertion tube, such as the shunt tube, in this application, or micro-electrodes, in the prior application. The insertion tube, therefore, will be connected to the drive mechanism using varying sized retention rings. The shunt will be directed towards the target established by the software mechanism alluded to above. The shunt tube will then be secured to the skull via mechanisms described in prior art, or via a compression fitting described above.

Alternatively, a biopsy probe can be inserted into the insertion tube by first placing a biopsy tube with a trocar/obturator through the insertion tube. The mechanism would then be directed down towards the appropriate target using the drive mechanism. The obturator would be removed, and a cutting blade will then be inserted into the biopsy tube.

In applications in which a radioactive seed for brachytherapy, a targeting nodule with a radio sensitizing, chemotherapeutic agent for external beam radiation, or a sustained release polymer drug or microdialysis capsule for local drug administration, are required for placement in a deep brain target, a different insertion tube can be connected to the drive mechanism 1110. A delivery catheter can be placed through the insertion tube. The whole mechanism can be directed towards the deep target using the software system as alluded to above. An insertion plunger can be used to insert the object of delivery and the system is then be removed after insertion of the object. A micro-endoscope can also be inserted through the insertion tube mechanism described above and deep brain structures can be visualized prior to excision or lesioning.

In certain surgical procedures, it is desirable to drive a surgical instrument along several parallel tracks. This is facilitated using x-y table 1150. Before an instrument is driven toward the target, an offset is adjusted using adjustment knobs 1061, and 1063. These knobs include markings that allow precise adjustment.

An example of a procedure using penetration of an instrument along parallel tracks involves mapping the electrical activity of a region of the brain. The surgical instrument in this case is a thin electrode that is repeatedly inserted to points on a two- or three-dimensional grid. At each point, electrical activity is monitored.

Referring to FIG. 17, when larger masses within the brain, such as brain tumors, have to be removed with precision, the drive mechanism has a localizing surgical retractor 1210 mounted in place of the insertion tube, and base platter 1220 has a large central opening through which the retractor passes. Retractor 1210 includes three or more spatulas 1212 inserted through base platter 1220 and the entry column. Each spatula 1212 includes a tracking LED 1214 attached to it. The relationship of the spatulas is controlled by a screw assembly 1216 that allows the relative distance between the spatulas to be modified. Relatively small movement at the screw assembly results in a larger movement at the other ends of the spatulas due to the pivoting of the spatulas within the retractor. Tracking LEDs 1214 are tracked by the camera array and the localization application computes the depth of spatulas 1212 and their displacement from the central axis.

Using the tracking approach described above, surgical localizing retractor 1210 is directed towards the brain target. Upon acquiring the target, screw assembly 1216 is adjusted to expand localizing retractor 1210 to allow visualization of the underlying brain. A variety of surgical instruments can be attached to retractor 1210 in addition to using the retractor with more conventional manual techniques. These instruments can include an endoscope, an ultrasonic aspirator, an electronic coagulation/evaporator/ablator, or a laser.

An optional fixture validation step (FIG. 1, step 130) can be used to confirm that the position of the tip of the surgical instrument is accurately tracked. Two types of validation can be performed. Referring to FIG. 18, guidance fixture 710 is attached to an upper mounting plate 1334 of a calibration jig 1330. Prior to attaching guidance fixture 710 to calibration jig 1330, pivoting locking knob 846 (FIG. 10) is loosened allowing pivoting collar 840 to pivot. After guidance fixture 710 is attached, pivoting collar 840 is centered and pivoting locking knob 846 is tightened. A guidance tube 1340 is clamped into the guidance fixture, and a surgical instrument 1342 is passed through the guidance tube. Guidance tube 1340 protrudes below upper mounting plate 1334. A ruler 1335 can then be used to measure the depth of penetration of the guidance tube. Similarly, ruler 1335 can be used to measure the penetration of surgical instrument 1342.

Referring to FIG. 19, a validation (or "phantom") jig 1312 can also be used. Tracking MIRRF 510 is attached to validation jig 1312. Guidance fixture 710 is mounted on validation jig 1312. A phantom target point 1320 at a known position relative to validation jig 1312, and therefore at a known position relative to the fiducial points on tracking MIRRF 510, is chosen. The localization application 588 is programmed with the phantom target position. Using the procedure that will be used during the surgical phase, the surgeon performs the registration and alignment steps and then drives the instrument through guidance fixture 710. If the tip of the instrument is coincident with the phantom target point, then guidance fixture 710 is validated. If for some reason the instrument is not coincident with the phantom target point, for example, due to improper attachment of the instrument to the drive assembly resulting in an incorrect depth calibration, the surgeon readjusts the instrument and attempts the validation step again.

Other embodiments of the invention use alternative scanning, registration, and tracking markers, and methods of scanning and registration.

In the first embodiment, scanning MIRRF 310 and tracking MIRRF 510 are star-shaped. Other alternative shapes of MIRRFs can be used. Referring to FIG. 20, an arc-shaped MIRRF 1410 is attached to threaded inserts 1420 using bolts 1430, and marking and locking nuts 1432. Arc-shaped MIRRF 1410 includes scanning fiducial markers 1412. The fiducial markers are more widely spaced than in star-shaped MIRRFs 310, and 510, resulting in a more accurate tracing of the MIRRF. During insertion of threaded inserts 1420, arc-shaped MIRRF 1410 acts as a template for accurate positioning of the threaded inserts.

In embodiments described above, threaded inserts are inserted into the skull to provide the fixed points of attachment for MIRRFs. Alternative embodiments use other types of anchors or forms of mechanical attachment. Protruding posts can be attached to the skull. A MIRRF is then attached to the posts. Also, inserts can be implanted in the skull which provide precisely positioned "divots." These divots are used to mate clamping posts on a MIRRF, which hold the MIRRF

in place. Such implanted divots can be covered by the skin and remain in place for an extended period of time.

An alternative to use of a MIRRF is to attach markers directly to anchors in the skull. Referring to FIG. 21, each such anchor, shown as threaded insert **1440**, can support a single scanning marker **1444** on a post **1442**, subsequently support a single registration divot **1450** on a second post **1451**, and then support a single tracking marker, LED **1448**, on a third post **1446**. The geometric relationship of the anchor to the scanning marker is the same as the geometric relationship of the anchor to the tracking marker thereby allowing a localization application to directly track the fiducial points by tracking the location of the tracking marker.

Using any of the MIRRF structures described, multiple MIRRFs can be used to provide increased accuracy in registration and tracking. For example, two star-shaped MIRRFs can be used, one on each side of the head.

In other embodiments, alternative attachment methods can be used to secure a guidance fixture to the skull. For instance, the mounting base can be relatively small and have extended "legs" extending radically and secured to the skin or skull with sharp points. These legs provide stabilization that may not be achievable using mounting screws through the smaller mounting base. The mounting base can alternatively include an insert that fits into the burr hole. This insert can also be threaded to allow direct attachment of the mounting base to the burr hole.

In other embodiments, threaded inserts are used to attach, and subsequently accurately reattach, conventional stereotactic frames. This allows the conventional stereotactic frame to be removed and then accurately reattached to the skull. Procedures, such as fractionated multi-day stereotactic radiation treatments could then be performed with the stereotactic frame being reattached for each treatment.

Referring to FIG. 22, a modified guidance fixture **1510** is used in combination with a conventional stereotactic frame **1520**. Guidance fixture **1510** includes an x-y positioning table with LEDs **1512** and an instrument drive with an LED **1514** for tracking the depth of the surgical instrument. The guidance assembly is positioned on frame **1520** to align with the planned surgical trajectory. A tracking MIRRF **1530** is attached to frame **1520** to allow dynamic tracking.

Rather than using a scanning MIRRF with scanning fiducial markers, or scanning fiducial markers attached directly to anchors embedded in the skull, alternative embodiments can use other features for registration. In one alternative embodiment, paste-on scanning markers are attached to the skin. During the registration phase, the cranial probe is positioned at each of the paste-on markers in turn, rather than at the fiducial points on a MIRRF. Tracking LEDs are attached in a fixed position relative to the skull in some other way than using a MIRRF, for example, using an elastic headband. Rather than using pasted on fiducial markers, another alternative embodiment uses accessible anatomical features. These features are located in the scanned image, and the probe is positioned at these features during the registration phase. Still another alternative does not use discrete fiducial points, but rather makes use of the surface shape of the skull in a "surface merge" approach. The surface of the skull is located in the three-dimensional image. During registration, the cranial probe touches a large number of points on the skull. The locations of these points is matched to the shape of the skull to determine the conformal mapping from the physical coordinate system to the image coordinate system.

In yet another embodiment, referring to FIG. 23, a tracking MIRRF **1610** can be attached directly to the base of a guidance fixture **710**. Tracking MIRRF **1610** is only useful for tracking after guidance fixture **710** has been attached to the skull. In this approach, registration is based on fiducial points elsewhere on the skull than tracking MIRRF **1610**.

Locating the entry point, over which guidance fixture **710** is attached can be accomplished using one of a variety of alternative techniques. For example, the entry point may be known for some standardized procedures. Alternatively, the entry point may be determined by registration of the skull and the three-dimensional image based on fiducial markers attached to the head, for example using adhesive pads, anatomical markers, or a "surface merge" technique as described above.

Once the guidance fixture and tracking MIRRF **1610** are attached to the skull, LEDs **1620** on tracking MIRRF **1610** are used to track the location of the skull, and thereby track the location of the surgical instrument. A reregistration step (FIG. 1, step **160**) can be performed to determine the relative position of the fiducial points to LEDs **1620**.

Various mechanical adjustments of guidance fixture **710**, if performed when an guidance tube is inserted in the brain, would potentially damage the brain tissue. The guidance fixture optionally includes a feature that the various locking knobs and x-y adjustment knobs are rotated using a removable knob (or key). When not in use, this knob is stowed on the drive assembly. Whenever the removable knob is removed from its stowed position, the signal from an electrical sensor on the drive assembly that is connected to the workstation causes a warning, for example on the computer display, to be provided to the surgeon.

Alternative related embodiments can make use of known geometric relationships of points on various devices. For instance, the relationship between the tip of a probe and the location of tracking LEDs can be calibrated and used by a localization application to compute the location of tip using the computed location the LEDs. Similarly, the relationship between the location of fiducial points on a MIRRF and tracking LEDs can be calibrated, thereby allowing a localization application to compute the coordinates of fiducial points from the coordinates of the tracking LEDs without using the registration procedure described above.

In the above embodiments, tracking LEDs are tracked using a camera. Other alternative embodiments can use other three-dimensional sensing and tracking approaches. Rather than LEDs, other tracking markers that are active emitters of electromagnetic or mechanical energy such as electronic sparks, heat, magnetic energy, or sound can be used. Appropriate three-dimensional tracking approaches, for example, using imaging or triangulation techniques determine the three-dimensional coordinates of the emitters. Alternatively, tracking markers that are passive reflectors or transducers of externally applied localizing energy, such as infrared light, sound, magnetism, can be used.

The devices described above can be made of a variety of materials. One alternative is to use a material, such as carbon fiber, which does not interfere with MRI scanning. This allows use of the devices during intraoperative MRI scanning. Also, use of hydraulic drive mechanisms rather than electrical motors avoids interference with MRI scanning.

In the surgical procedures described above, the patient is not necessary immobilized. It may be desirable, however, to immobilize the patient, for example by clamping the guidance fixture to an operating table, at some times during the surgery.

It is to be understood that the foregoing description is intended to illustrate and not limit the scope of the invention, which is defined by the scope of the appended claims. Other aspects, advantages, and modifications are within the scope of the following claims.

What is claimed is:

1. A rigid scanning frame for stereotactic surgery on a body on which a plurality of anchors are affixed in a fixed geometric relationship comprising:

a plurality of scanning markers affixed to the scanning frame at a plurality of locations on said frame for making corresponding images in a scanned image of the body; and

a plurality of positioning elements arranged on the scanning frame in a fixed geometric relationship such that each of the plurality of positioning elements is attachable to a different one of the plurality of anchors and the locations of the scanning markers are predetermined in relation to the anchors when the scanning frame is attached to the anchors on the body.

2. The scanning frame of claim 1 wherein the number of the plurality of scanning markers is greater than the number of the plurality of positioning elements of the scanning frame.

3. The scanning frame of claim 1 wherein the scanning frame is made of a material that is substantially invisible in a scanned image of the body in which the scanning markers are visible.

4. The scanning frame of claim 3 wherein the material is polycarbonate.

5. The scanning frame of claim 3 wherein the material is carbon fiber.

6. A kit for stereotactic surgery on a body on which a plurality of anchors are affixed in a fixed geometric relationship comprising:

a rigid scanning frame including a plurality of scanning markers affixed to the scanning frame at a plurality of locations on said frame for making corresponding images in a scanned image of the body, and a plurality of positioning elements arranged on the scanning frame in a fixed geometric relationship such that each of the plurality of positioning elements is attachable to a different one of the plurality of anchors and the loca-

tions of the scanning markers are predetermined in relation to the anchors when the scanning frame is attached to the anchors on the body; and

a rigid tracking frame including a plurality of tracking markers for tracking a position of the frame using a remote sensing device, and a plurality of positioning elements arranged on the tracking frame in a fixed geometric relationship such that each of the plurality of positioning elements is attachable to a different one of the plurality of anchors when the tracking frame is attached to the anchors on the body.

7. The kit of claim 6 wherein the number of the plurality of tracking markers is greater than the number of the plurality of positioning elements of the tracking frame.

8. The kit of claim 6 wherein each of the positioning elements in the tracking frame includes a hole in the tracking frame for passing a fastener through the hole and into a corresponding one of the anchors.

9. The kit of claim 6 wherein each of the positioning elements in the tracking frame includes a post that mates with a corresponding one of the anchors.

10. The kit of claim 6 wherein each of the plurality of tracking markers includes a light emitting diode.

11. The kit of claim 6 wherein the tracking frame includes a plurality of position indicators in the same geometric relationship to the positioning elements on the tracking frame as the geometric relationship between the scanning markers and the positioning elements on the scanning frame.

12. The kit of claim 6 wherein the locations of the tracking markers are predetermined in relation to the anchors when the tracking frame is attached to the body.

13. The kit of claim 6 wherein the tracking frame includes a central part and a plurality of arms rigidly attached to and extending from the central part.

14. The kit of claim 13 wherein the plurality of arms includes four arms arranged in a cross shape.

15. The kit of claim 14 wherein at least one of the arms is longer than the other arms.

16. The kit of claim 11 wherein each of the position indicators includes a divot in the surface of the tracking frame.

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UNITED STATES PATENT AND TRADEMARK OFFICE
Certificate

Patent No. 6,273,896 B1

Patented: August 14, 2001

On petition requesting issuance of a certificate for correction of inventorship pursuant to 35 U.S.C. 256, it has been found that the above identified patent, through error and without any deceptive intent, improperly sets forth the inventorship.

Accordingly, it is hereby certified that the correct inventorship of this patent is: Joel I. Franck, Durham, ME (US); Frederick C. Haer, Brunswick, ME (US); Ronald J. Franklin, Bowdoinham, ME (US); Kevin J. Frank, Lafayette, CO (US); and John B. Clayton, IV, Northborough, MA (US).

Signed and Sealed this Third Day of April 2007.

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