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(54) SYSTEMS AND METHODS FOR A SPATIAL QUANTITATIVE AND ANATOMICALLY ACCURATE SURGICAL CORRIDOR MODELING PLATFORM

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(60) Provisional application No. 63/185,081, filed on May 6, 2021.

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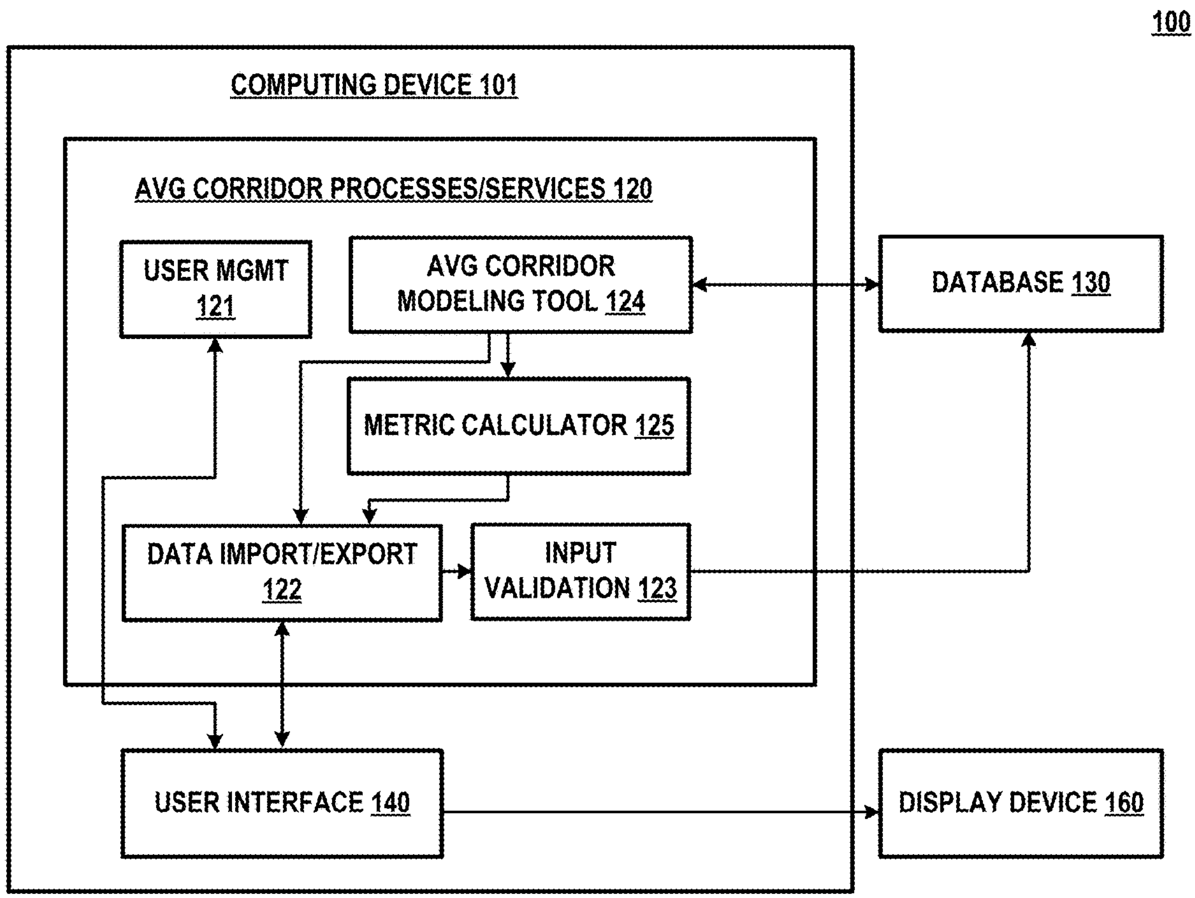
G06T 19/00	(2011.01)
G06T 19/20	(2011.01)

(52) **U.S. Cl.**

CPC ***G16H 20/40*** (2018.01); ***A61B 34/10*** (2016.02); ***G06T 17/30*** (2013.01); ***G06T 19/003*** (2013.01); ***G06T 19/20*** (2013.01); *A61B 2034/104* (2016.02); *A61B 2034/105* (2016.02); *A61B 2034/107* (2016.02); *G06T 2210/41* (2013.01); *G06T 2219/2004* (2013.01)

(57) **ABSTRACT**

Various embodiments of a system and associated method for modeling an average surgical corridor based on a plurality of datasets are disclosed herein.



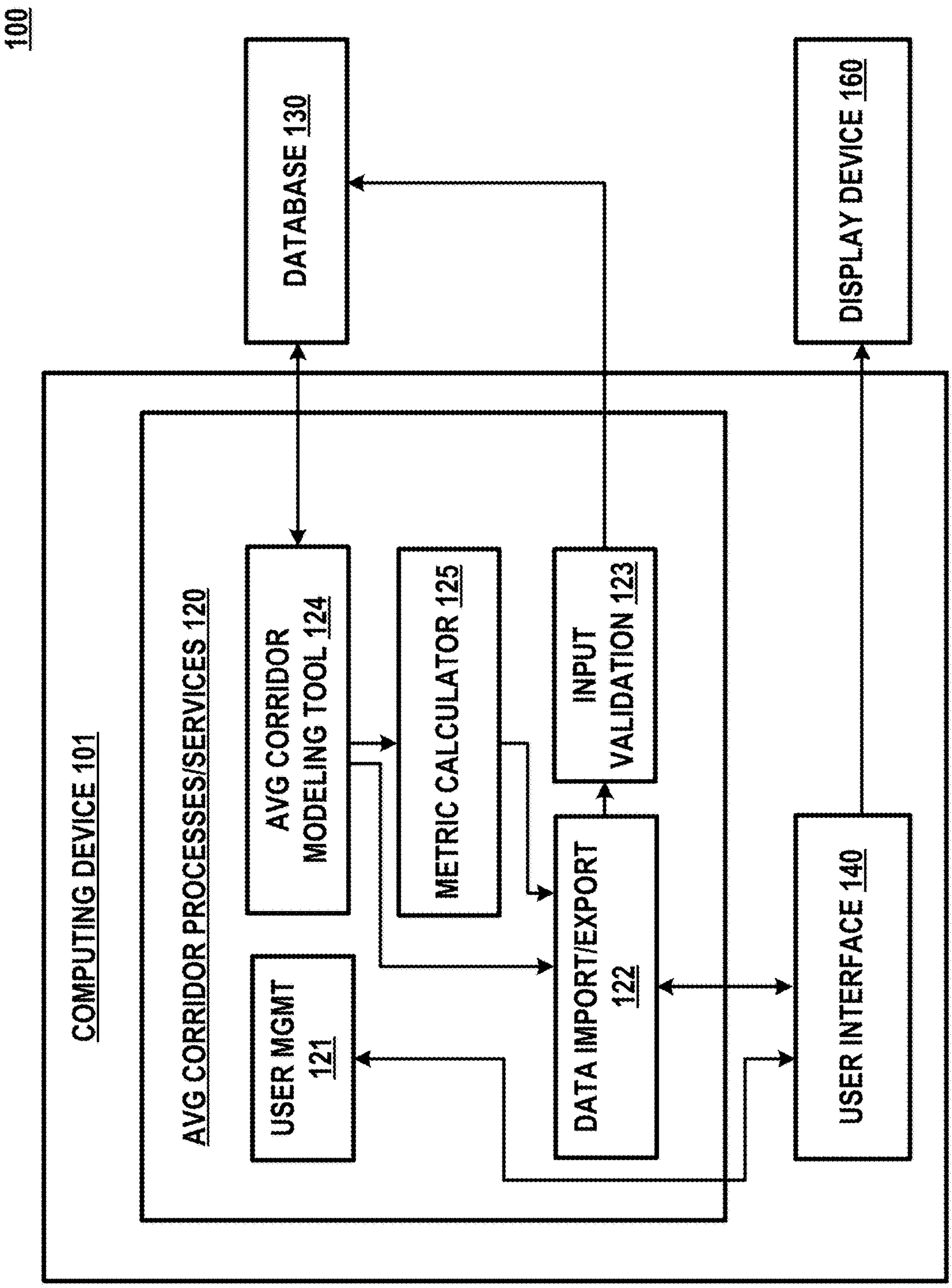

100
DATABASE 130
DISPLAY DEVICE 160
COMPUTING DEVICE 101
AVG CORRIDOR PROCESSES/SERVICES 120
AVG CORRIDOR MODELING TOOL 124
METRIC CALCULATOR 125
INPUT VALIDATION 123
USER MGMT 121
DATA IMPORT/EXPORT 122
USER INTERFACE 140

FIG. 1A

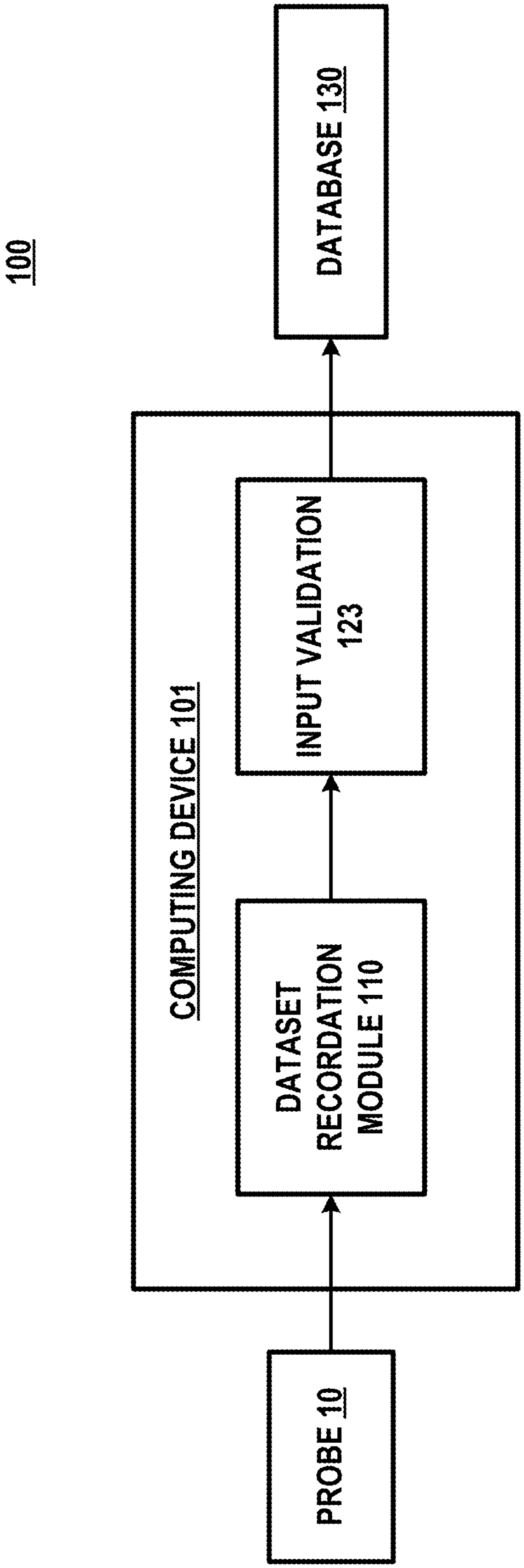

100
PROBE 10
COMPUTING DEVICE 101
DATASET RECORDATION MODULE 110
INPUT VALIDATION 123
DATABASE 130

FIG. 1B

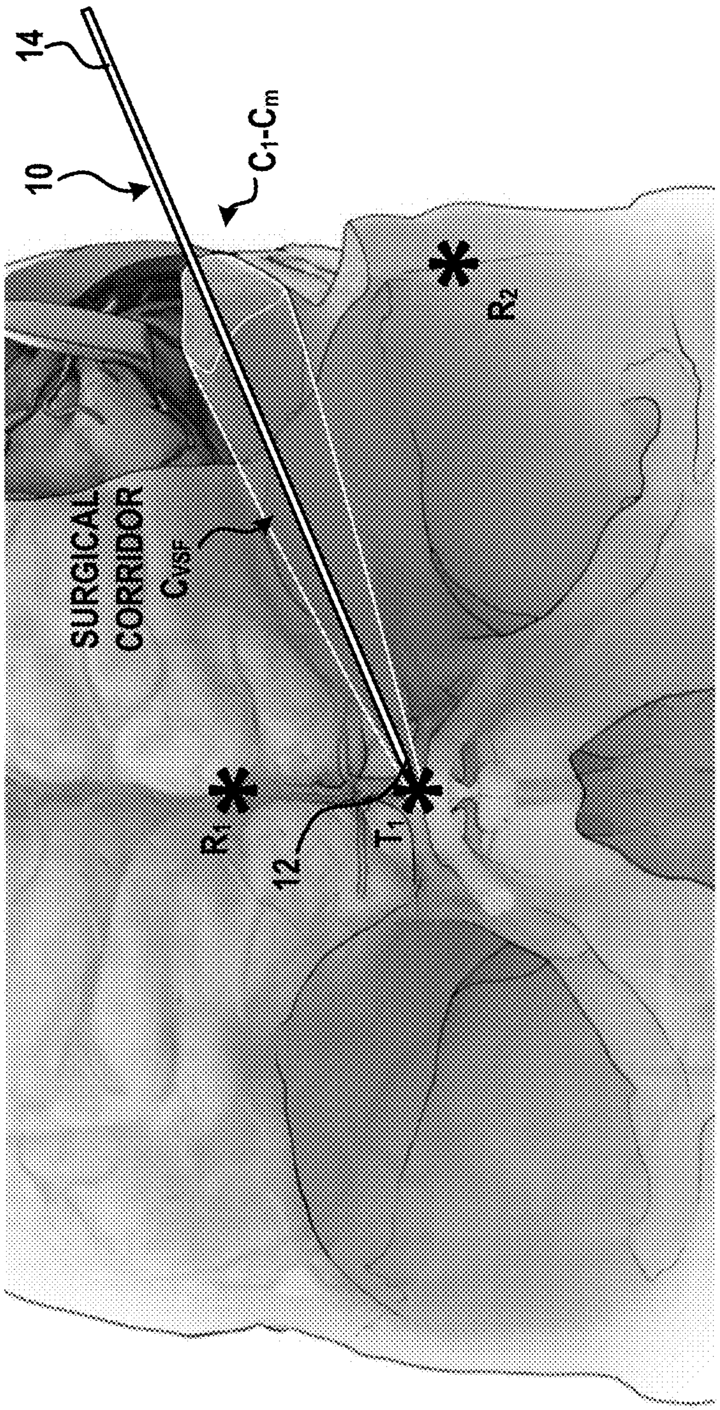


FIG. 2

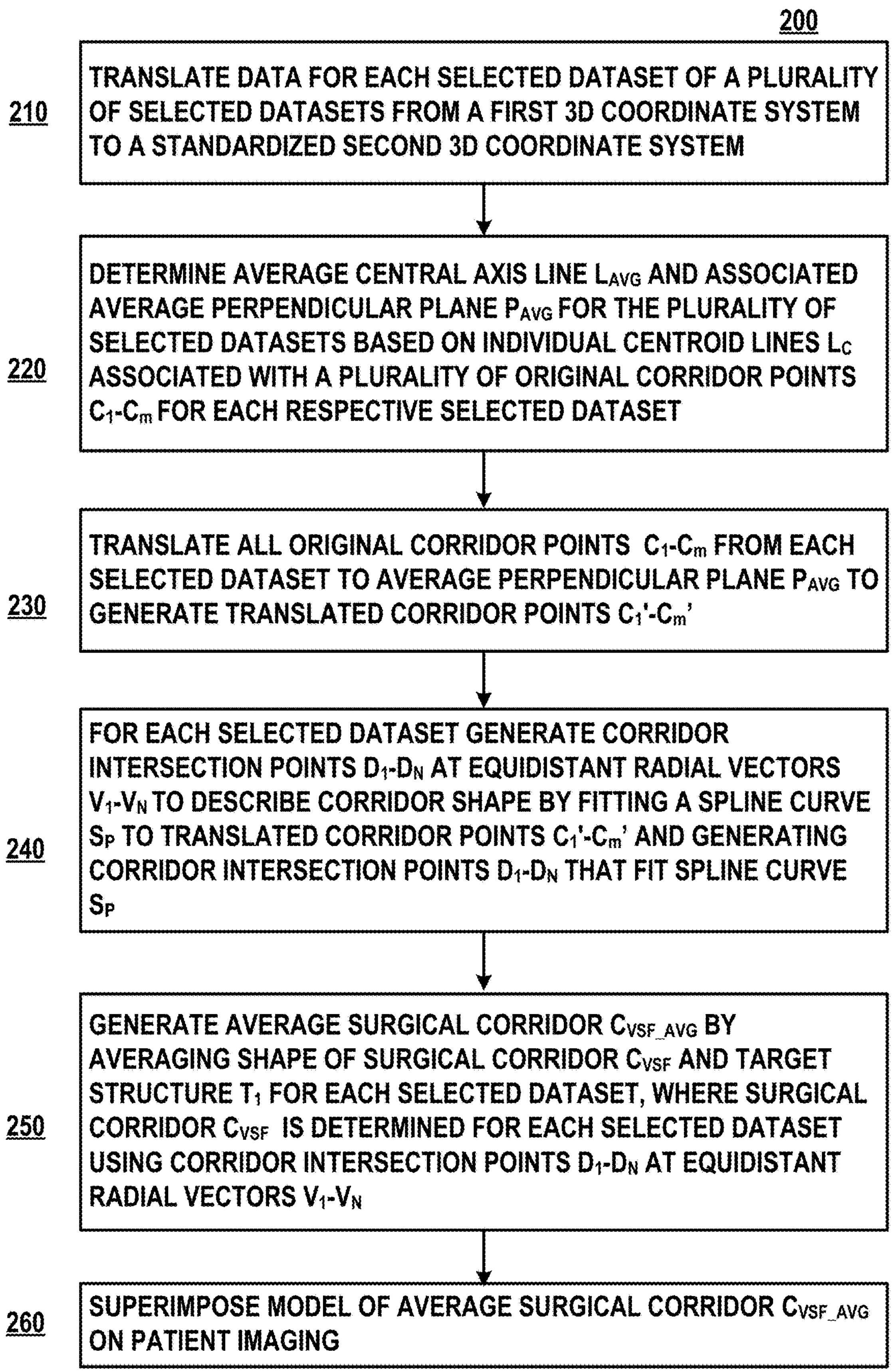

200
210
TRANSLATE DATA FOR EACH SELECTED DATASET OF A PLURALITY OF SELECTED DATASETS FROM A FIRST 3D COORDINATE SYSTEM TO A STANDARDIZED SECOND 3D COORDINATE SYSTEM
220
DETERMINE AVERAGE CENTRAL AXIS LINE L_{AVG} AND ASSOCIATED AVERAGE PERPENDICULAR PLANE P_{AVG} FOR THE PLURALITY OF SELECTED DATASETS BASED ON INDIVIDUAL CENTROID LINES L_C ASSOCIATED WITH A PLURALITY OF ORIGINAL CORRIDOR POINTS C_1-C_m FOR EACH RESPECTIVE SELECTED DATASET
230
TRANSLATE ALL ORIGINAL CORRIDOR POINTS C_1-C_m FROM EACH SELECTED DATASET TO AVERAGE PERPENDICULAR PLANE P_{AVG} TO GENERATE TRANSLATED CORRIDOR POINTS C_1'-C_m'
240
FOR EACH SELECTED DATASET GENERATE CORRIDOR INTERSECTION POINTS D_1-D_N AT EQUIDISTANT RADIAL VECTORS V_1-V_N TO DESCRIBE CORRIDOR SHAPE BY FITTING A SPLINE CURVE S_P TO TRANSLATED CORRIDOR POINTS C_1'-C_m' AND GENERATING CORRIDOR INTERSECTION POINTS D_1-D_N THAT FIT SPLINE CURVE S_P
250
GENERATE AVERAGE SURGICAL CORRIDOR C_{VSF_AVG} BY AVERAGING SHAPE OF SURGICAL CORRIDOR C_{VSF} AND TARGET STRUCTURE T_1 FOR EACH SELECTED DATASET, WHERE SURGICAL CORRIDOR C_{VSF} IS DETERMINED FOR EACH SELECTED DATASET USING CORRIDOR INTERSECTION POINTS D_1-D_N AT EQUIDISTANT RADIAL VECTORS V_1-V_N
260
SUPERIMPOSE MODEL OF AVERAGE SURGICAL CORRIDOR C_{VSF_AVG} ON PATIENT IMAGING

FIG. 3

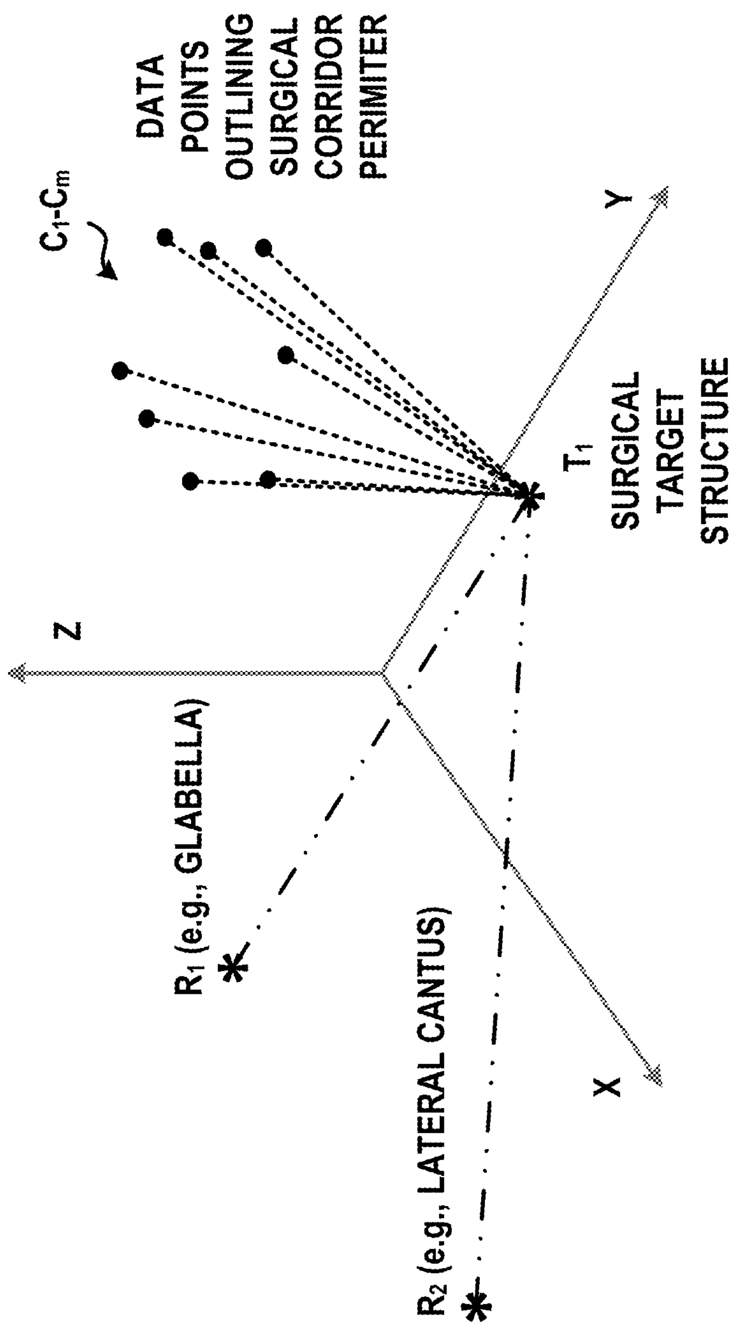

DATA
POINTS
OUTLINING
SURGICAL
CORRIDOR
PERIMITER
C_1-C_m
Y
Z
X
T_1
SURGICAL
TARGET
STRUCTURE
R_1 (e.g., GLABELLA)
R_2 (e.g., LATERAL CANTUS)

FIG. 4

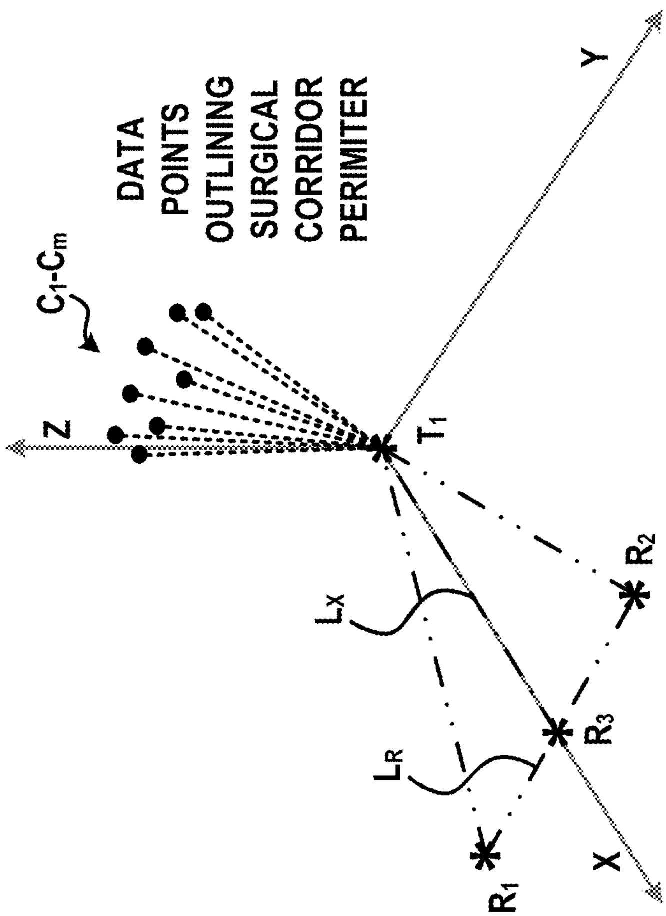

DATA
POINTS
OUTLINING
SURGICAL
CORRIDOR
PERIMITER
C_1-C_m
Z
Y
X
T_1
R_1
R_2
R_3
L_X
L_R

FIG. 5

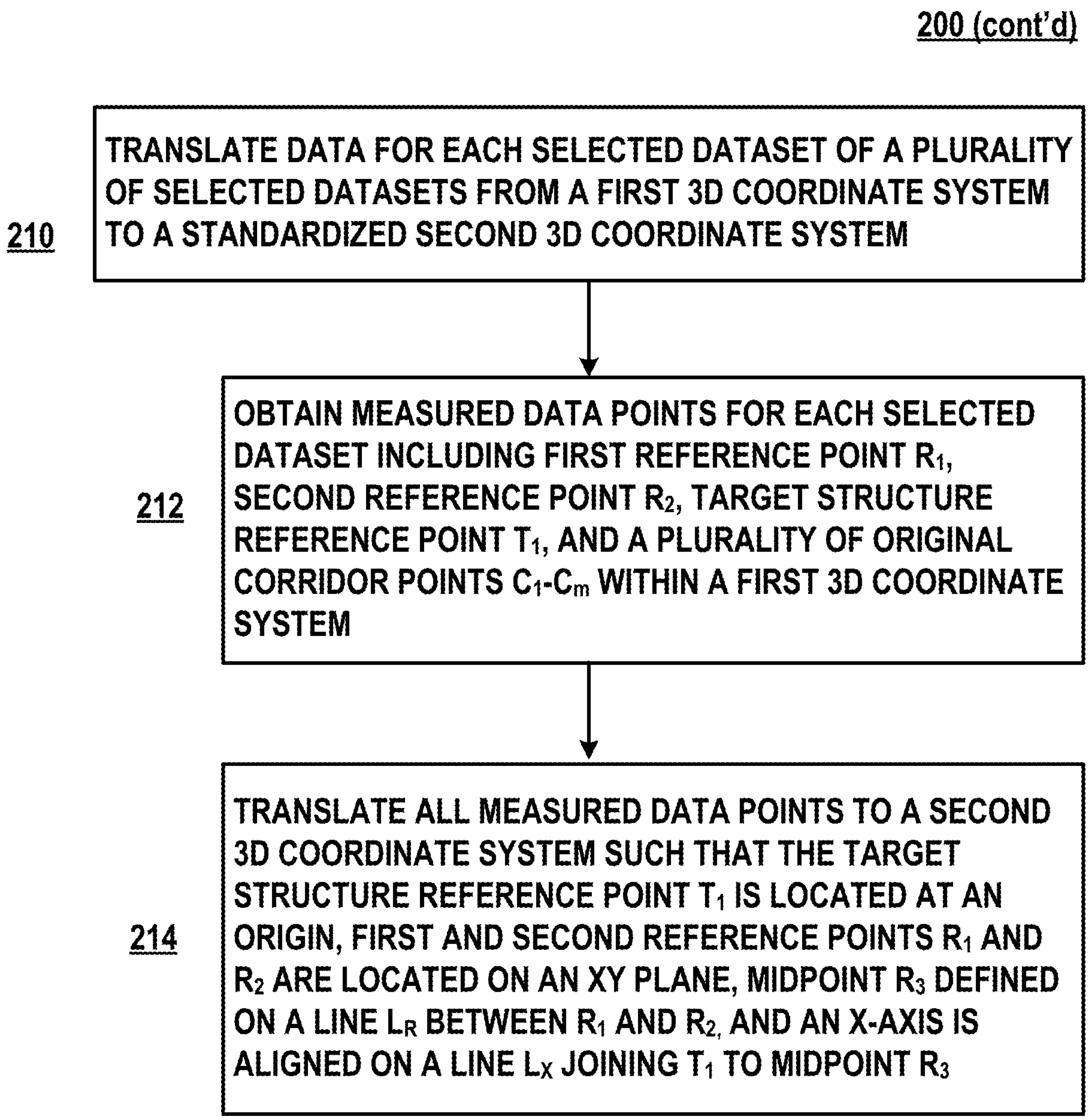

200 (cont'd)
210
TRANSLATE DATA FOR EACH SELECTED DATASET OF A PLURALITY OF SELECTED DATASETS FROM A FIRST 3D COORDINATE SYSTEM TO A STANDARDIZED SECOND 3D COORDINATE SYSTEM
212
OBTAIN MEASURED DATA POINTS FOR EACH SELECTED DATASET INCLUDING FIRST REFERENCE POINT R_1, SECOND REFERENCE POINT R_2, TARGET STRUCTURE REFERENCE POINT T_1, AND A PLURALITY OF ORIGINAL CORRIDOR POINTS C_1-C_m WITHIN A FIRST 3D COORDINATE SYSTEM
214
TRANSLATE ALL MEASURED DATA POINTS TO A SECOND 3D COORDINATE SYSTEM SUCH THAT THE TARGET STRUCTURE REFERENCE POINT T_1 IS LOCATED AT AN ORIGIN, FIRST AND SECOND REFERENCE POINTS R_1 AND R_2 ARE LOCATED ON AN XY PLANE, MIDPOINT R_3 DEFINED ON A LINE L_R BETWEEN R_1 AND R_2, AND AN X-AXIS IS ALIGNED ON A LINE L_X JOINING T_1 TO MIDPOINT R_3

FIG. 6

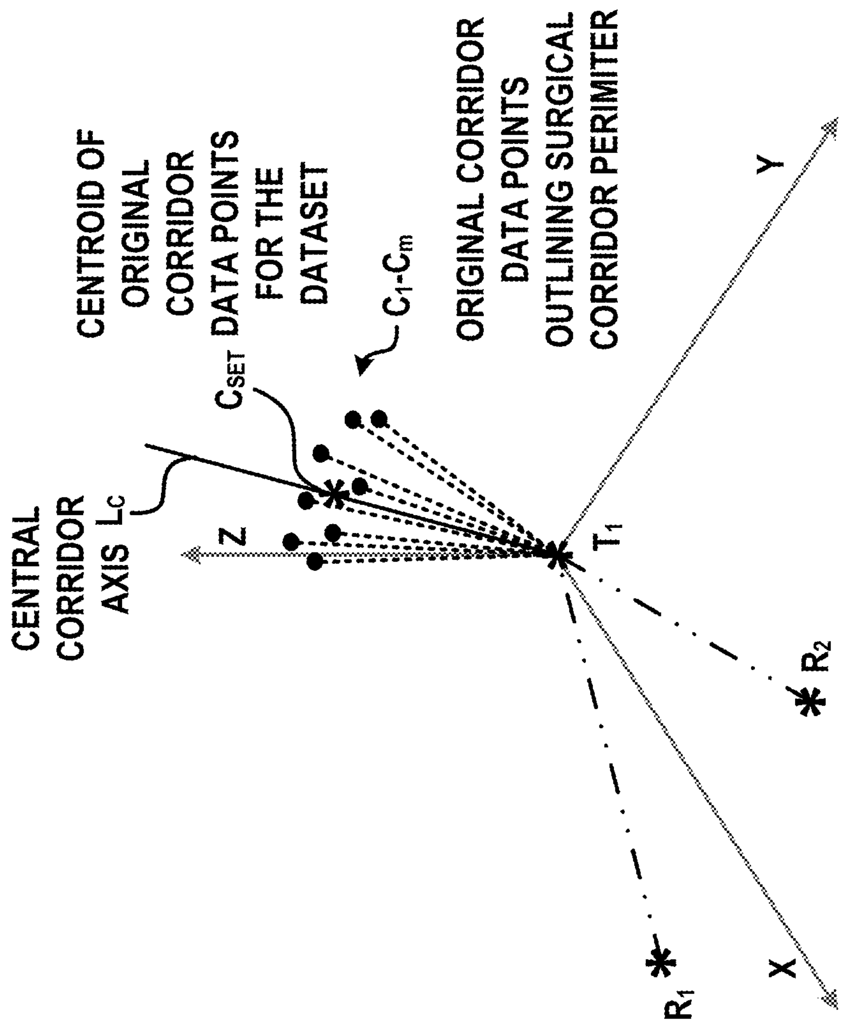

CENTRAL CORRIDOR AXIS L_C
Z
CENTROID OF ORIGINAL CORRIDOR DATA POINTS FOR THE DATASET
C_{SET}
C_1-C_m
ORIGINAL CORRIDOR DATA POINTS OUTLINING SURGICAL CORRIDOR PERIMITER
Y
T_1
R_2
R_1
X

FIG. 7

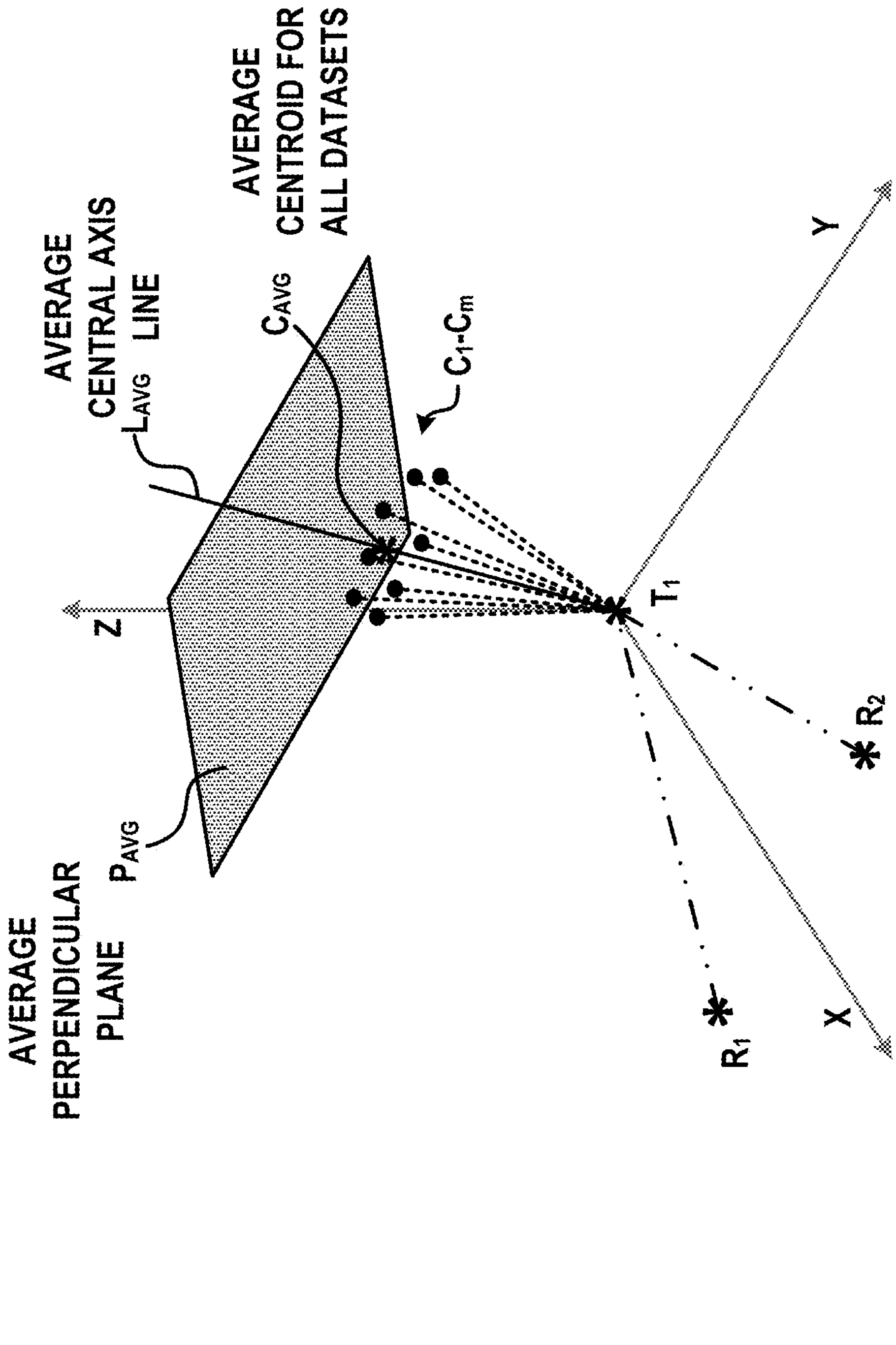

AVERAGE PERPENDICULAR PLANE
P_{AVG}
AVERAGE CENTRAL AXIS LINE
L_{AVG}
AVERAGE CENTROID FOR ALL DATASETS
C_{AVG}
C_1-C_m
Z
Y
X
T_1
R_1
R_2

FIG. 8

200 (cont'd)

220 DETERMINE AVERAGE CENTRAL AXIS LINE L_{AVG} AND ASSOCIATED AVERAGE PERPENDICULAR PLANE P_{AVG} FOR THE PLURALITY OF SELECTED DATASETS BASED ON INDIVIDUAL CENTROID LINES L_C ASSOCIATED WITH THE PLURALITY OF ORIGINAL CORRIDOR POINTS C_1-C_m FOR EACH RESPECTIVE SELECTED DATASET

↓

222 FOR EACH SELECTED DATASET, DETERMINE A CENTROID C_{SET} OF ORIGINAL CORRIDOR POINTS C_1-C_m AND DETERMINE CENTROID LINE L_C BETWEEN C_{SET} AND TARGET STRUCTURE T_1

↓

224 DETERMINE AN AVERAGE CENTROID C_{AVG} OF ALL CENTROIDS C_{SET} OF THE PLURALITY OF SELECTED DATASETS AND DETERMINE AVERAGE CENTRAL AXIS LINE L_{AVG} BETWEEN C_{AVG} AND TARGET STRUCTURE T_1

↓

226 DETERMINE AN AVERAGE PERPENDICULAR PLANE P_{AVG} PERPENDICULAR TO AVERAGE CENTRAL AXIS LINE L_{AVG} AT A PREDETERMINED DISTANCE FROM TARGET STRUCTURE T_1

FIG. 9

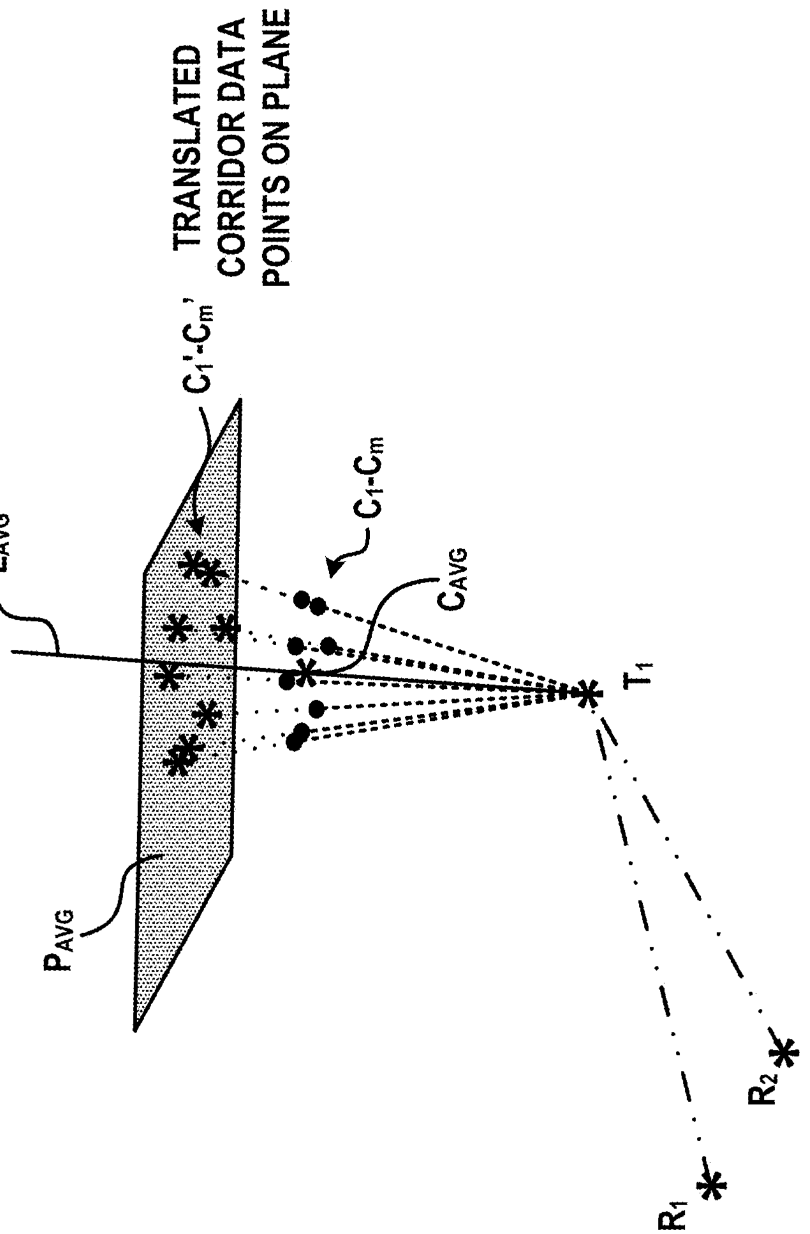

TRANSLATED
CORRIDOR DATA
POINTS ON PLANE
C_1'-C_m'
L_{AVG}
C_1-C_m
C_{AVG}
P_{AVG}
T_1
R_1
R_2

FIG. 10

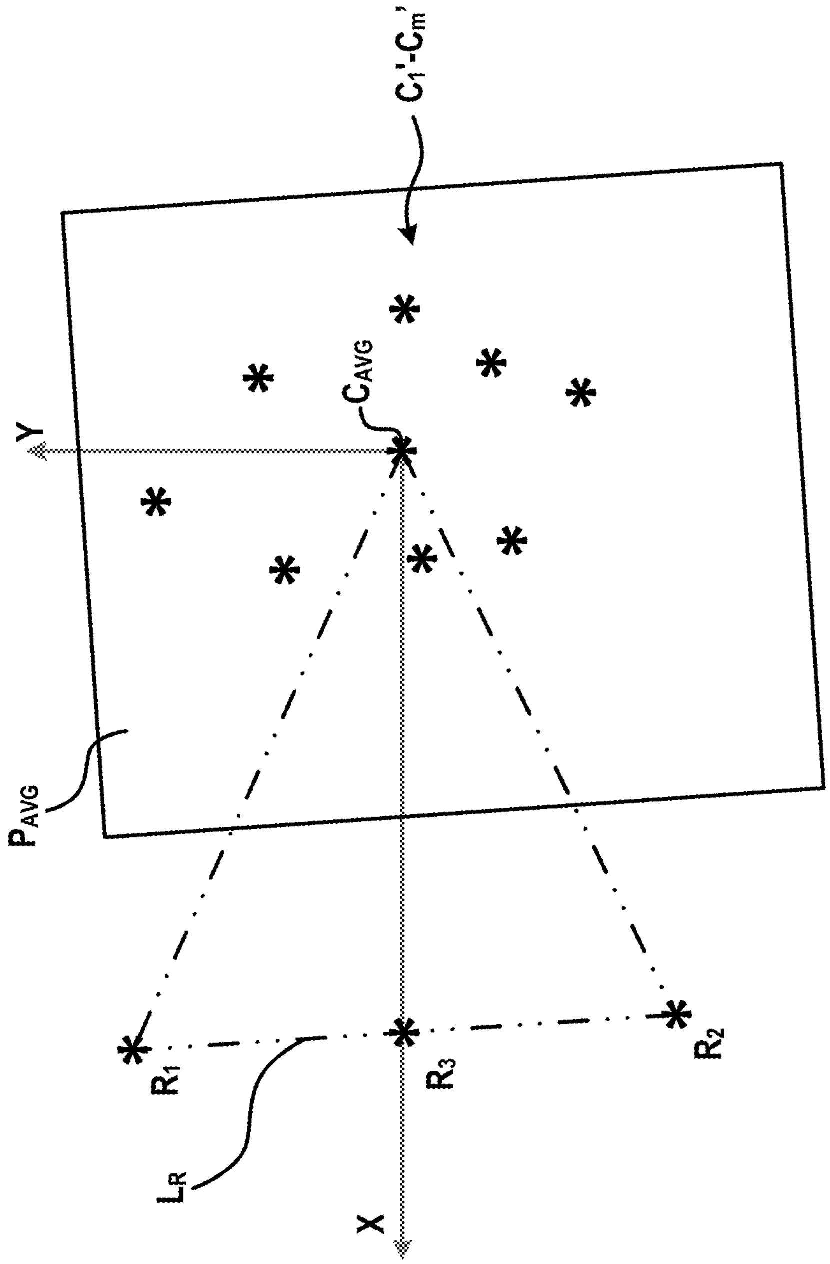


FIG. 11

200 (cont'd)

230 TRANSLATE ALL ORIGINAL CORRIDOR POINTS C_1-C_m FROM EACH SELECTED DATASET TO AVERAGE PERPENDICULAR PLANE P_{AVG} TO GENERATE TRANSLATED CORRIDOR POINTS C_1'-C_m'

↓

232 DETERMINE VECTOR BETWEEN TARGET STRUCTURE T_1 AND EACH ORIGINAL CORRIDOR POINT C_1-C_m AND TRANSLATE EACH ORIGINAL CORRIDOR POINT C_1-C_m TO THE AVERAGE PERPENDICULAR PLANE P_{AVG} TO BECOME TRANSLATED CORRIDOR POINTS C_1'-C_m'

↓

234 DEFINE FIRST 2D COORDINATE SYSTEM ON PERPENDICULAR PLANE P_{AVG} WITH TRANSLATED CORRIDOR POINTS C_1'-C_m'

FIG. 12

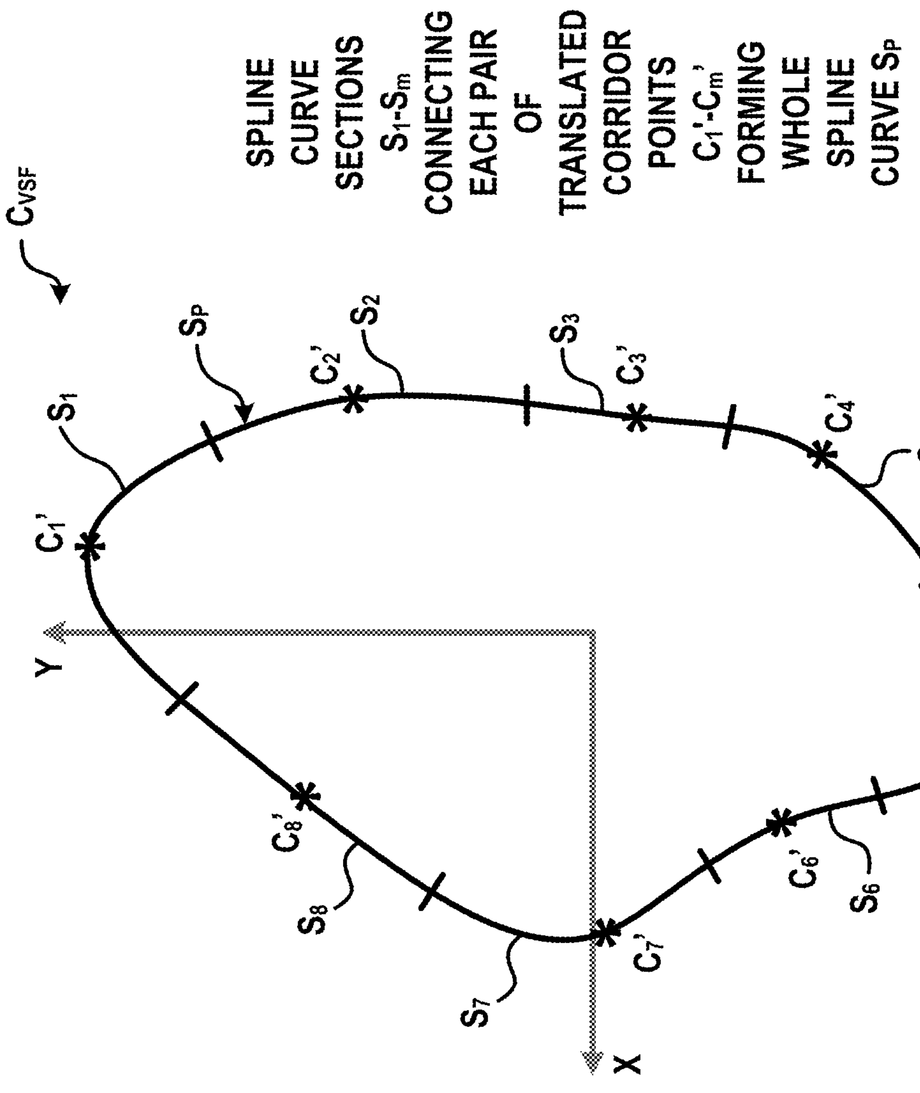

C_{VSF}
SPLINE CURVE SECTIONS S_1-S_m CONNECTING EACH PAIR OF TRANSLATED CORRIDOR POINTS C_1'-C_m' FORMING WHOLE SPLINE CURVE S_P
S_P
S_1
S_2
S_3
S_4
S_5
S_6
S_7
S_8
C_1'
C_2'
C_3'
C_4'
C_5'
C_6'
C_7'
C_8'
Y
X

FIG. 13

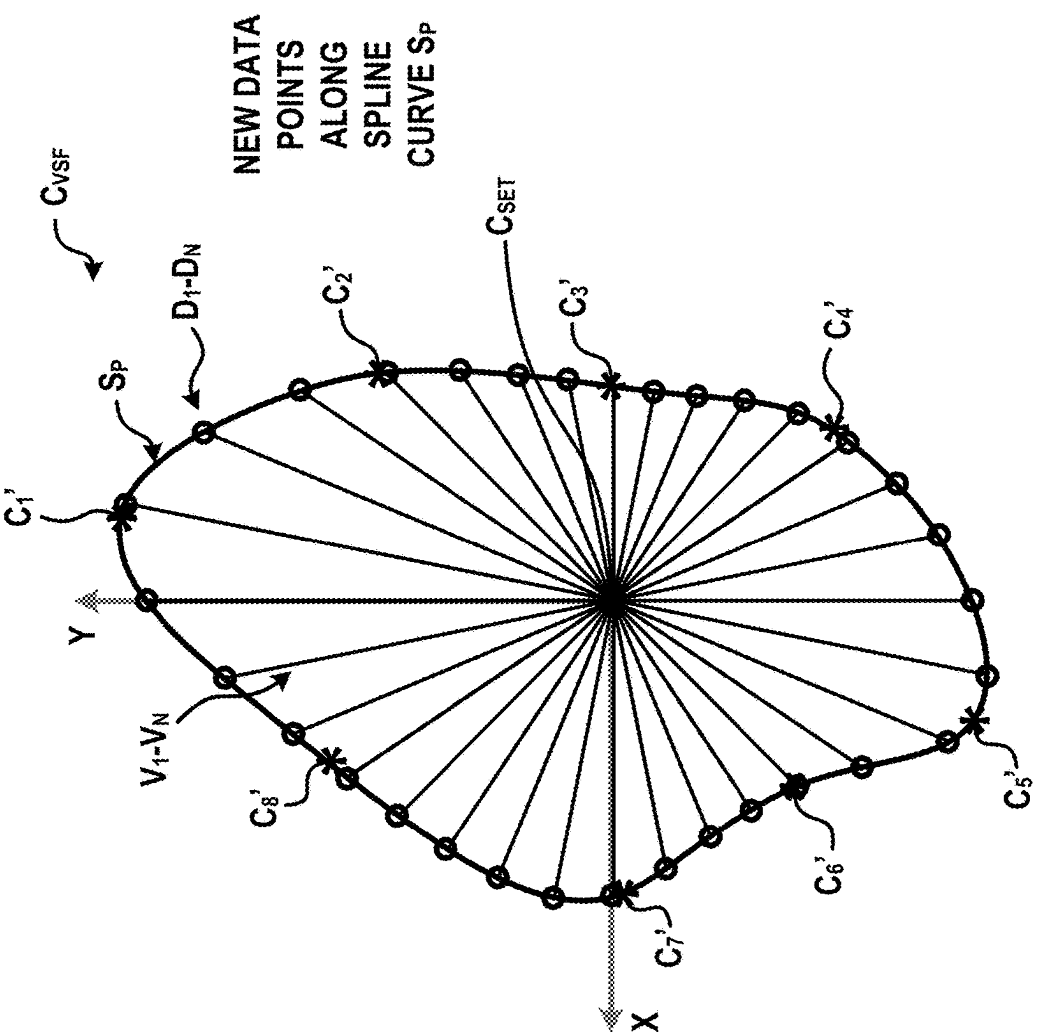

C_{VSF}
NEW DATA POINTS ALONG SPLINE CURVE S_P
C_{SET}
D_1-D_N
S_P
C_1'
C_2'
C_3'
C_4'
C_5'
C_6'
C_7'
C_8'
V_1-V_N
Y
X

FIG. 14

200 (cont'd)

240 FOR EACH SELECTED DATASET GENERATE CORRIDOR INTERSECTION POINTS D_1-D_N AT EQUIDISTANT RADIAL VECTORS V_1-V_N TO DESCRIBE CORRIDOR SHAPE BY FITTING A SPLINE CURVE S_P TO TRANSLATED CORRIDOR POINTS C_1'-C_m' AND GENERATE CORRIDOR INTERSECTION POINTS D_1-D_N THAT FIT SPLINE CURVE S_P

↓

242 GENERATE PIECEWISE SPLINE CURVE S_P TO FIT TO TRANSLATED CORRIDOR POINTS C_1'-C_m' WHERE EACH SPLINE CURVE SECTION S_t WHERE $t \in \{1, \ldots, m\}$ OF SPLINE CURVE S_P IS DEFINED BY A RESPECTIVE 3^{RD} DEGREE POLYNOMIAL

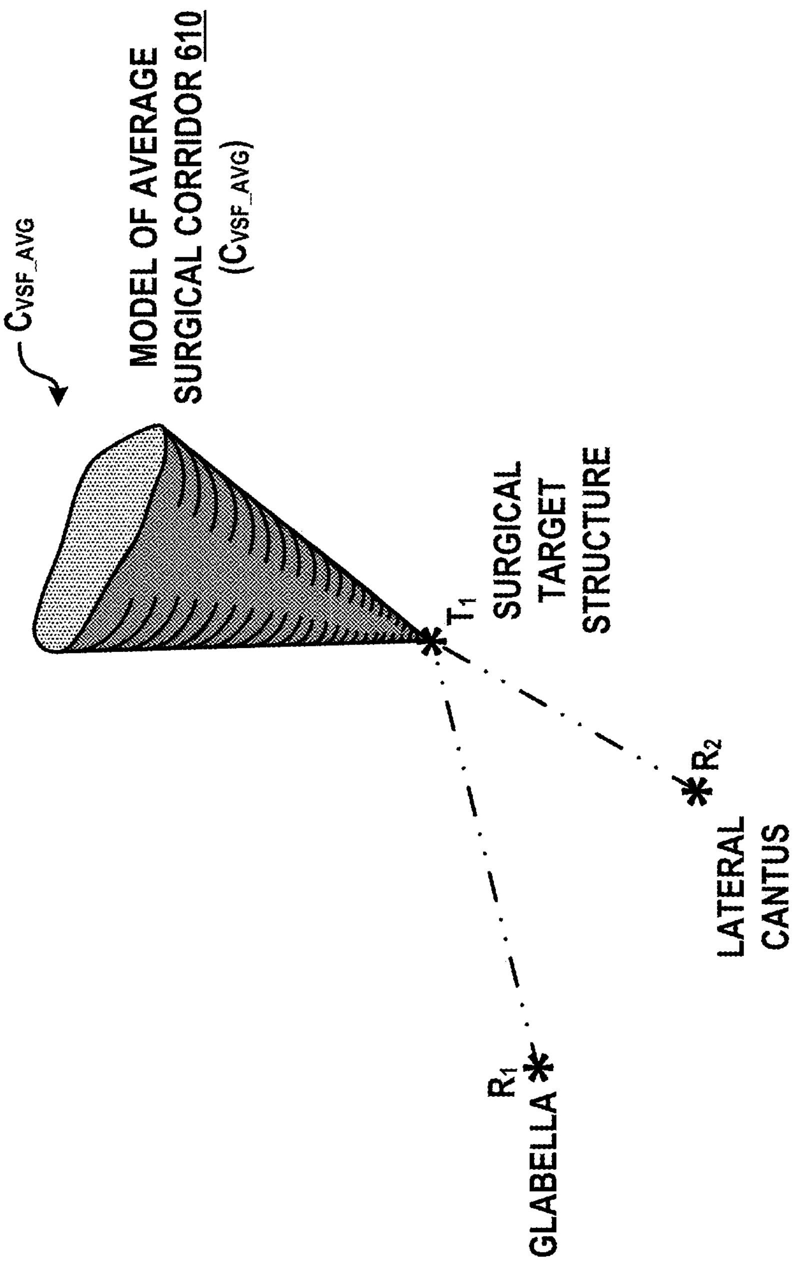
↓

244 GENERATE EQUDISTANT RADIAL VECTORS V_1-V_N EMANATING FROM CENTROID C_{SET} TO INTERSECT WITH SPLINE CURVE S_P

↓

246 GENERATE CORRIDOR INTERSECTION POINTS D_1-D_N AT RESPECTIVE INTERSECTIONS BETWEEN EQUIDISTANT RADIAL VECTORS V_1-V_N AND SPLINE CURVE S_P

FIG. 15



C_{VSF_AVG}
MODEL OF AVERAGE SURGICAL CORRIDOR 610
(C_{VSF_AVG})
T_1
SURGICAL TARGET STRUCTURE
R_2
LATERAL CANTUS
R_1
GLABELLA

FIG. 16

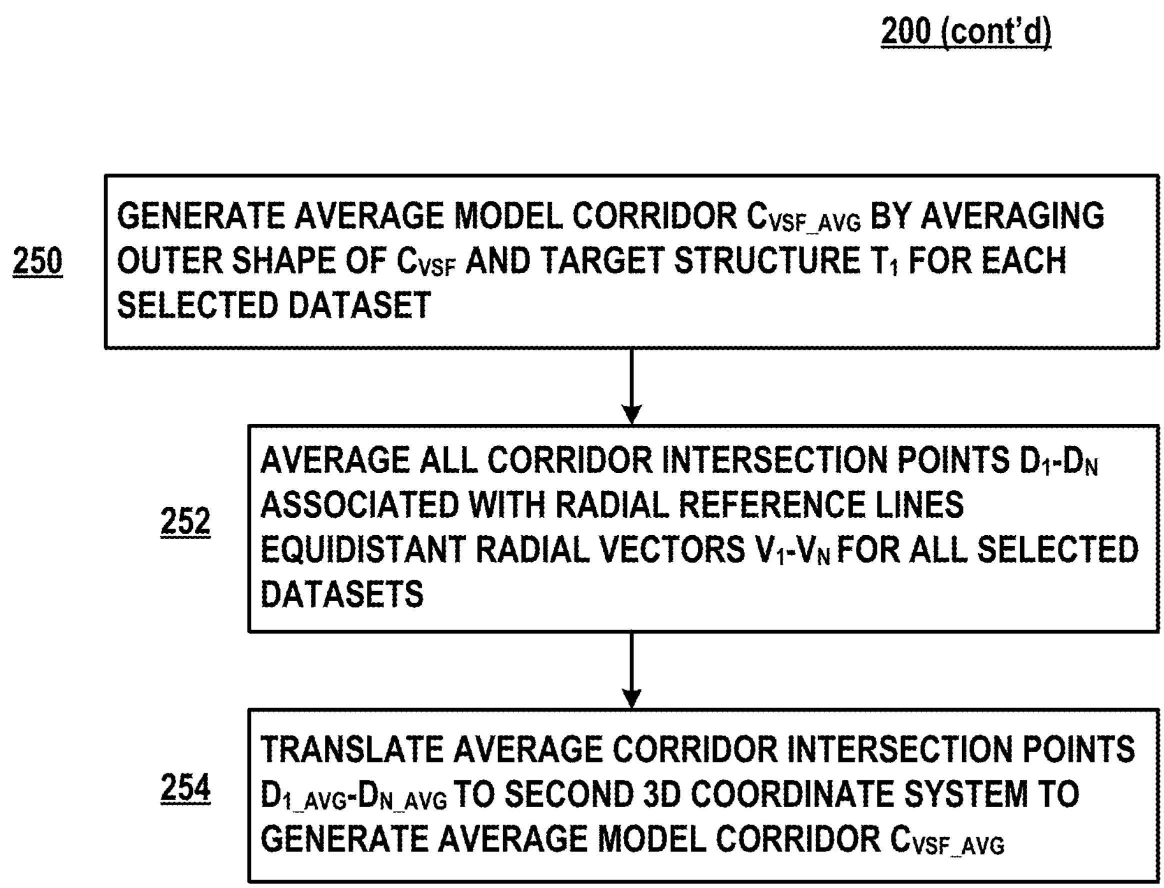

200 (cont'd)
250
GENERATE AVERAGE MODEL CORRIDOR C_{VSF_AVG} BY AVERAGING OUTER SHAPE OF C_{VSF} AND TARGET STRUCTURE T_1 FOR EACH SELECTED DATASET
252
AVERAGE ALL CORRIDOR INTERSECTION POINTS D_1-D_N ASSOCIATED WITH RADIAL REFERENCE LINES EQUIDISTANT RADIAL VECTORS V_1-V_N FOR ALL SELECTED DATASETS
254
TRANSLATE AVERAGE CORRIDOR INTERSECTION POINTS D_{1_AVG}-D_{N_AVG} TO SECOND 3D COORDINATE SYSTEM TO GENERATE AVERAGE MODEL CORRIDOR C_{VSF_AVG}

FIG. 17

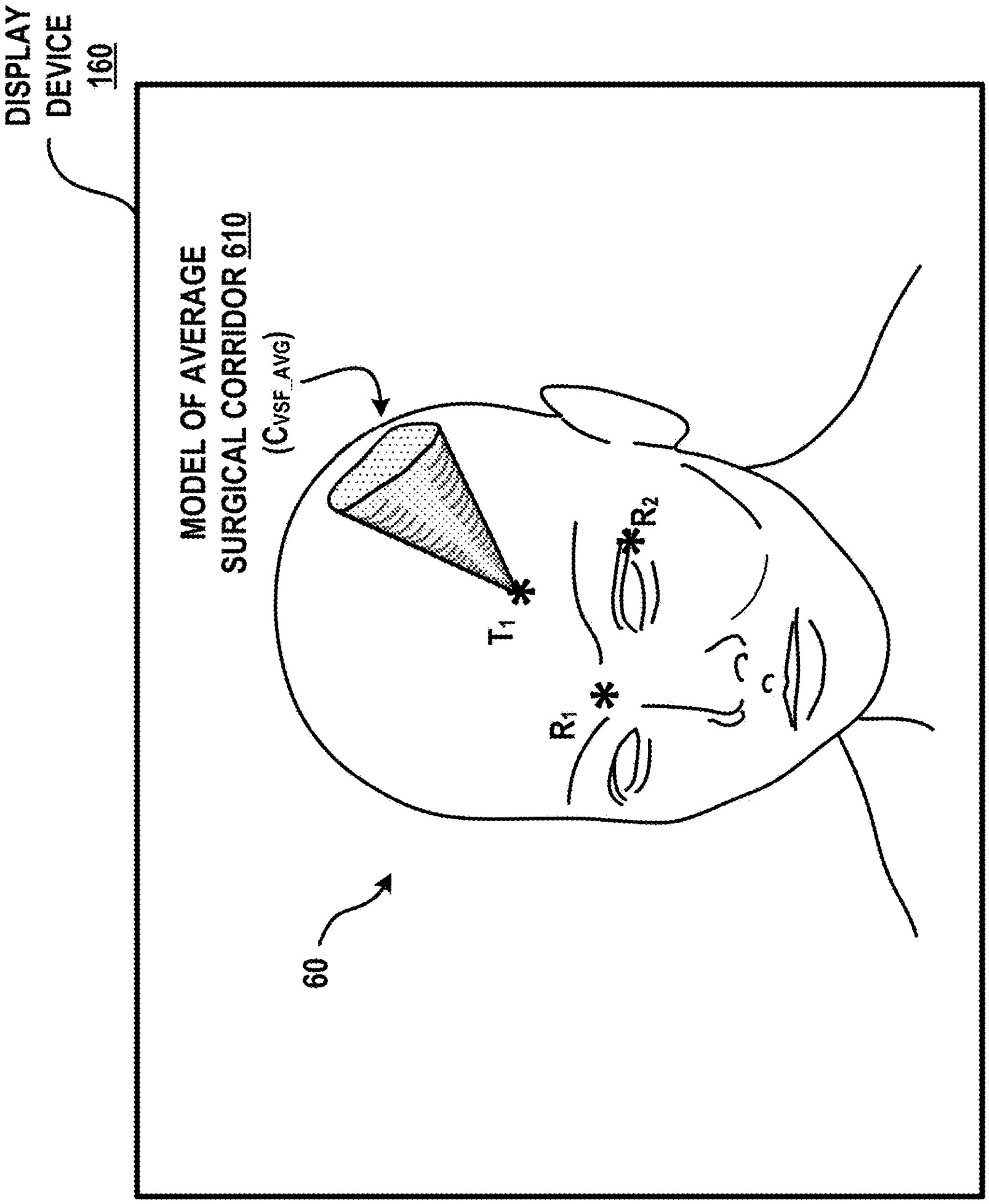

DISPLAY DEVICE 160
MODEL OF AVERAGE SURGICAL CORRIDOR 610
(C_{VSF_AVG})
T_1
R_1
R_2
C
60

FIG. 18A

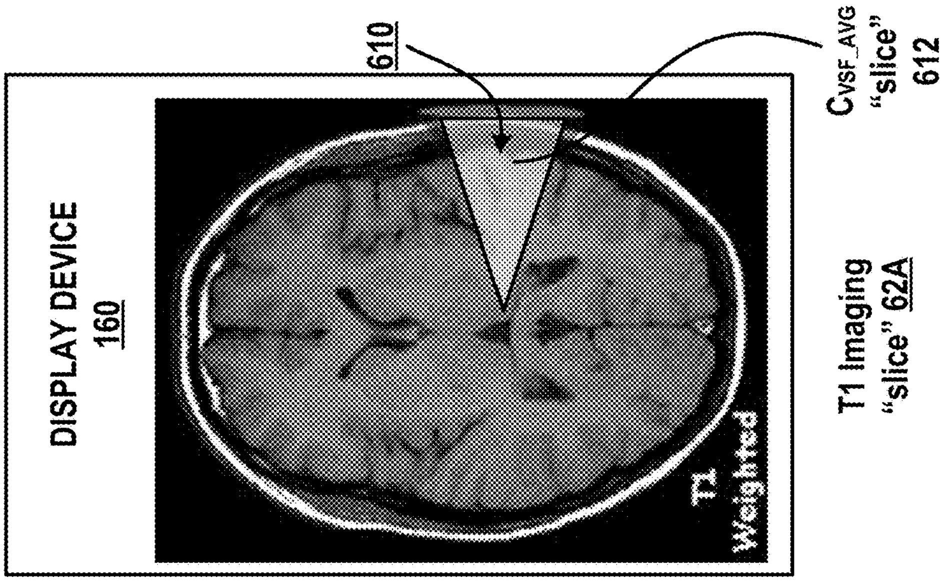


FIG. 18B

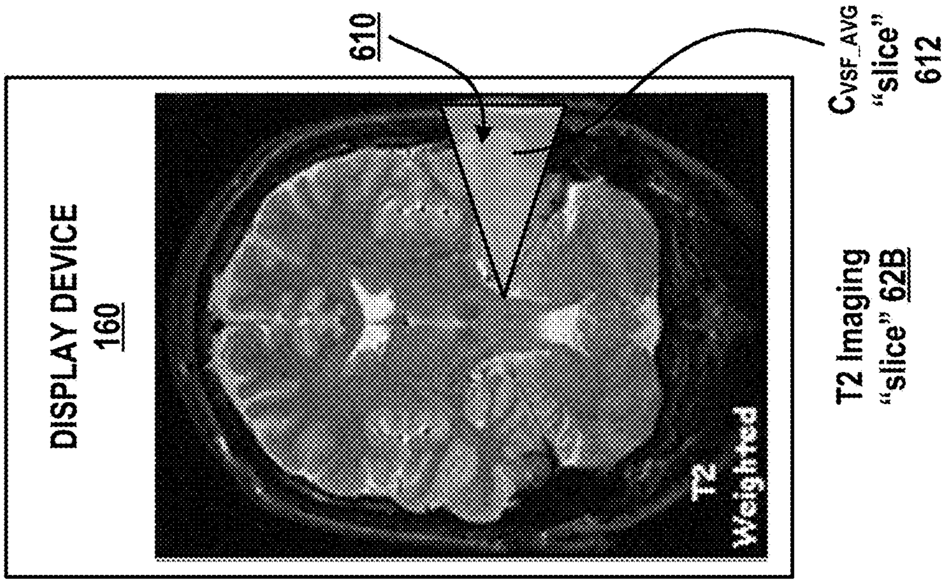


FIG. 18C

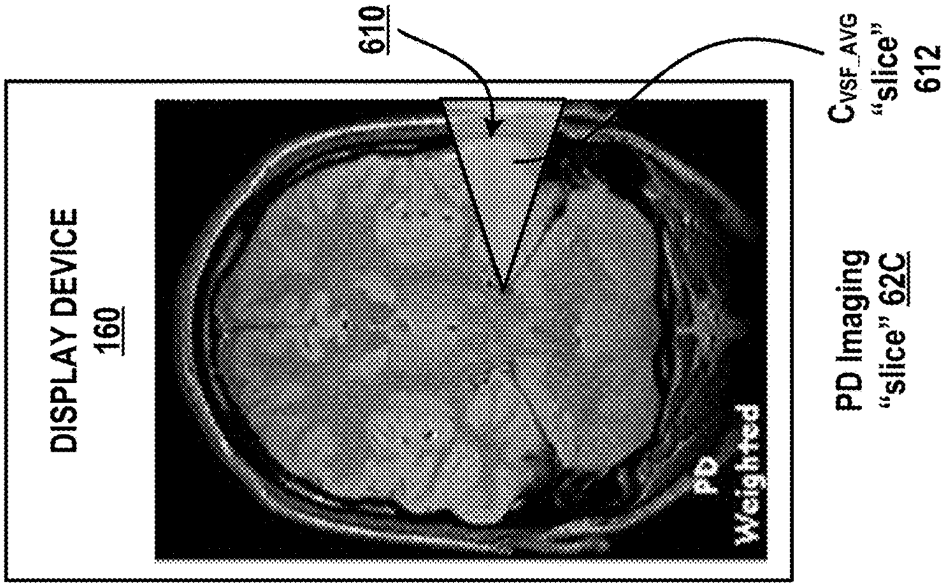


FIG. 18D

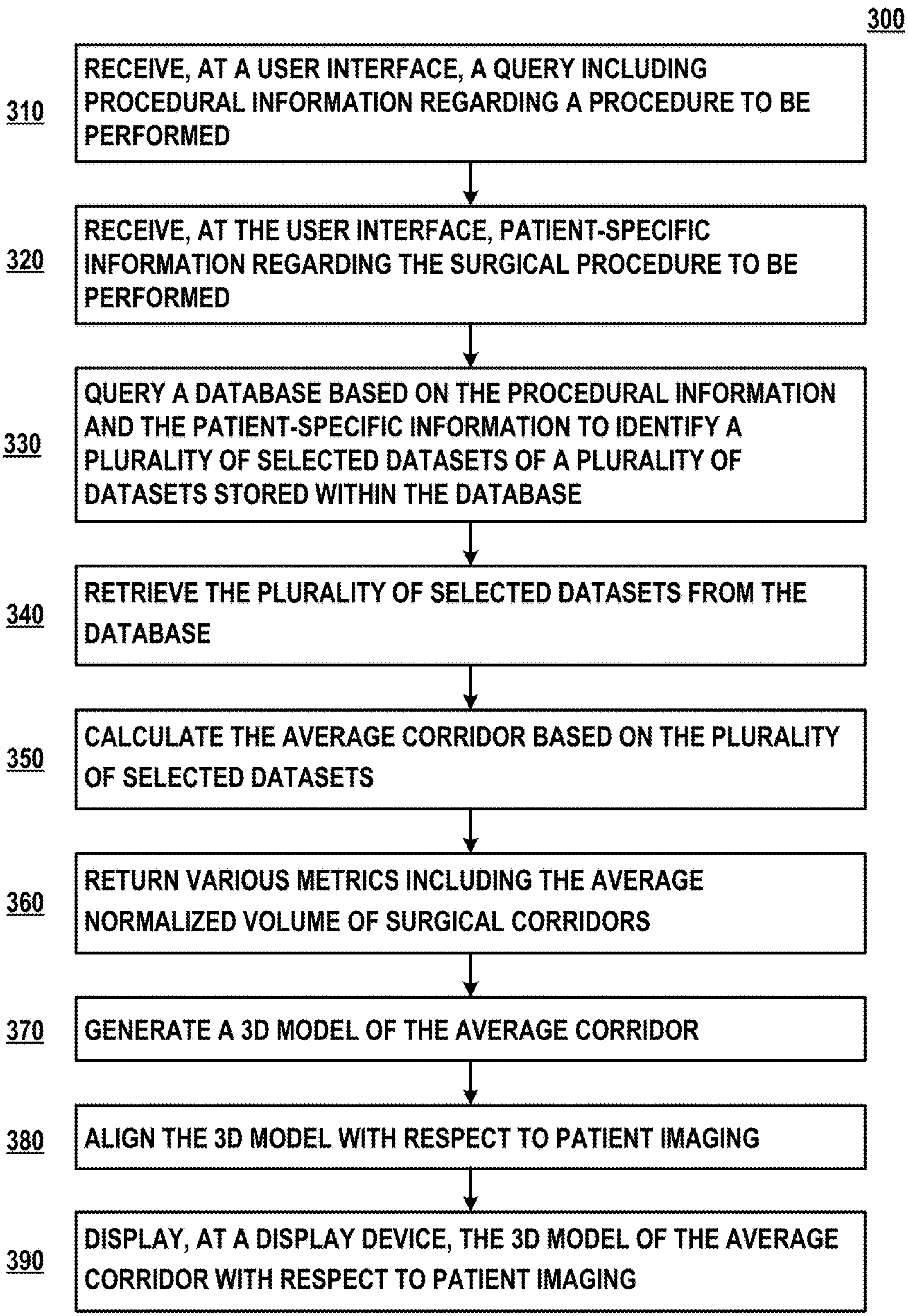

300
310
RECEIVE, AT A USER INTERFACE, A QUERY INCLUDING PROCEDURAL INFORMATION REGARDING A PROCEDURE TO BE PERFORMED
320
RECEIVE, AT THE USER INTERFACE, PATIENT-SPECIFIC INFORMATION REGARDING THE SURGICAL PROCEDURE TO BE PERFORMED
330
QUERY A DATABASE BASED ON THE PROCEDURAL INFORMATION AND THE PATIENT-SPECIFIC INFORMATION TO IDENTIFY A PLURALITY OF SELECTED DATASETS OF A PLURALITY OF DATASETS STORED WITHIN THE DATABASE
340
RETRIEVE THE PLURALITY OF SELECTED DATASETS FROM THE DATABASE
350
CALCULATE THE AVERAGE CORRIDOR BASED ON THE PLURALITY OF SELECTED DATASETS
360
RETURN VARIOUS METRICS INCLUDING THE AVERAGE NORMALIZED VOLUME OF SURGICAL CORRIDORS
370
GENERATE A 3D MODEL OF THE AVERAGE CORRIDOR
380
ALIGN THE 3D MODEL WITH RESPECT TO PATIENT IMAGING
390
DISPLAY, AT A DISPLAY DEVICE, THE 3D MODEL OF THE AVERAGE CORRIDOR WITH RESPECT TO PATIENT IMAGING

FIG. 19

DATABASE 130

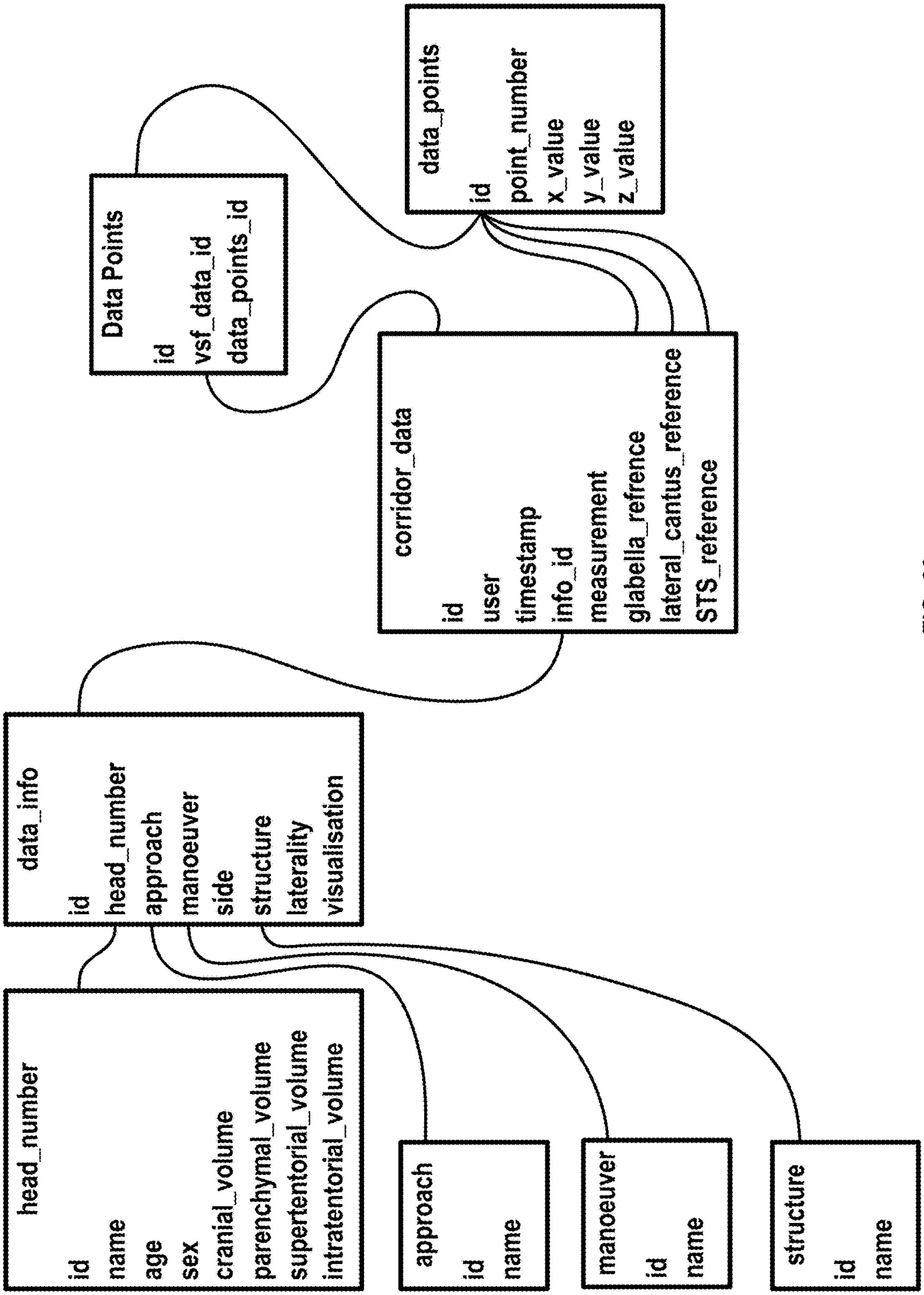


FIG. 20

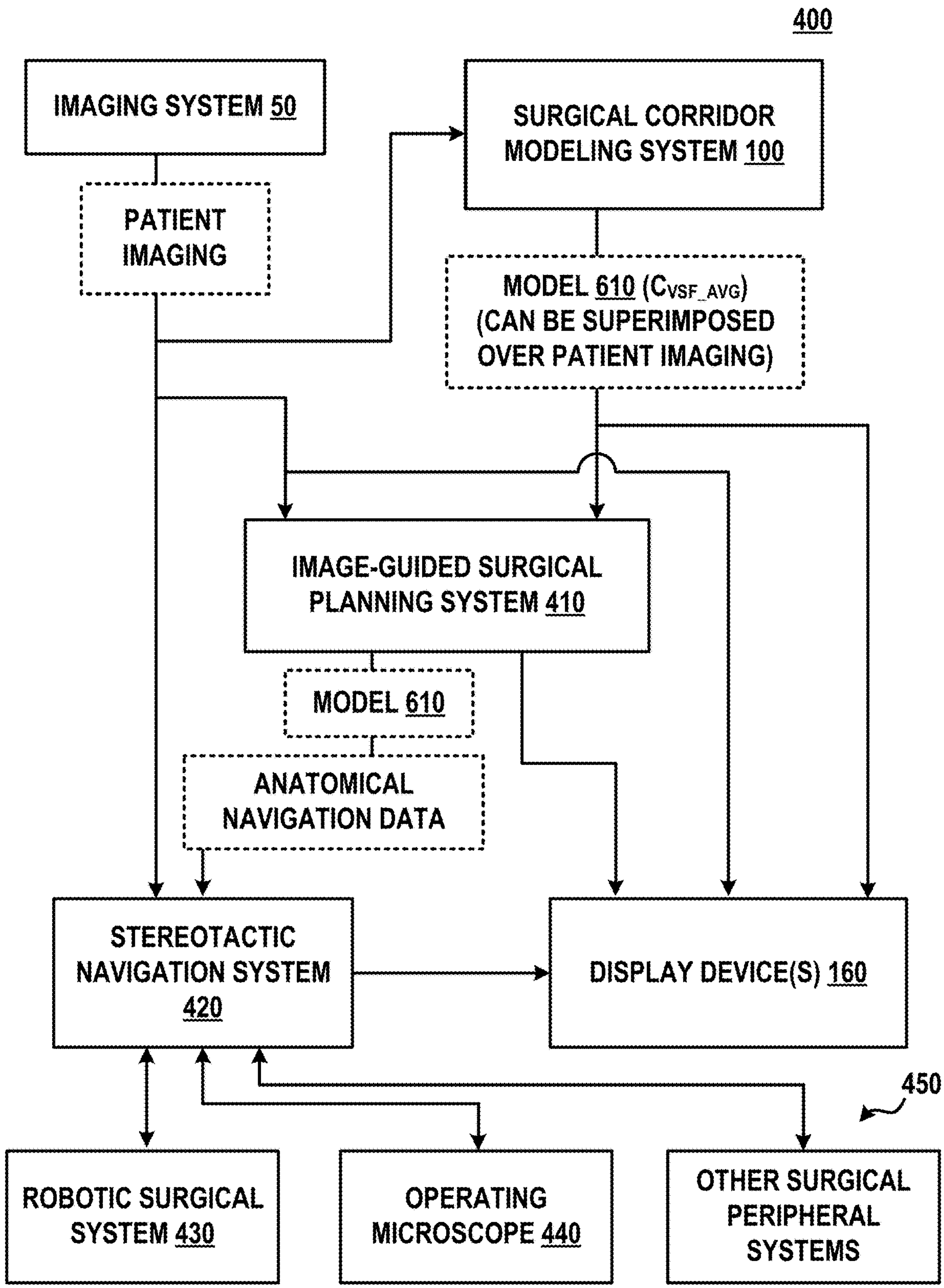

400
IMAGING SYSTEM 50
SURGICAL CORRIDOR MODELING SYSTEM 100
PATIENT IMAGING
MODEL 610 (C_{VSF_AVG}) (CAN BE SUPERIMPOSED OVER PATIENT IMAGING)
IMAGE-GUIDED SURGICAL PLANNING SYSTEM 410
MODEL 610
ANATOMICAL NAVIGATION DATA
STEREOTACTIC NAVIGATION SYSTEM 420
DISPLAY DEVICE(S) 160
450
ROBOTIC SURGICAL SYSTEM 430
OPERATING MICROSCOPE 440
OTHER SURGICAL PERIPHERAL SYSTEMS

FIG. 21

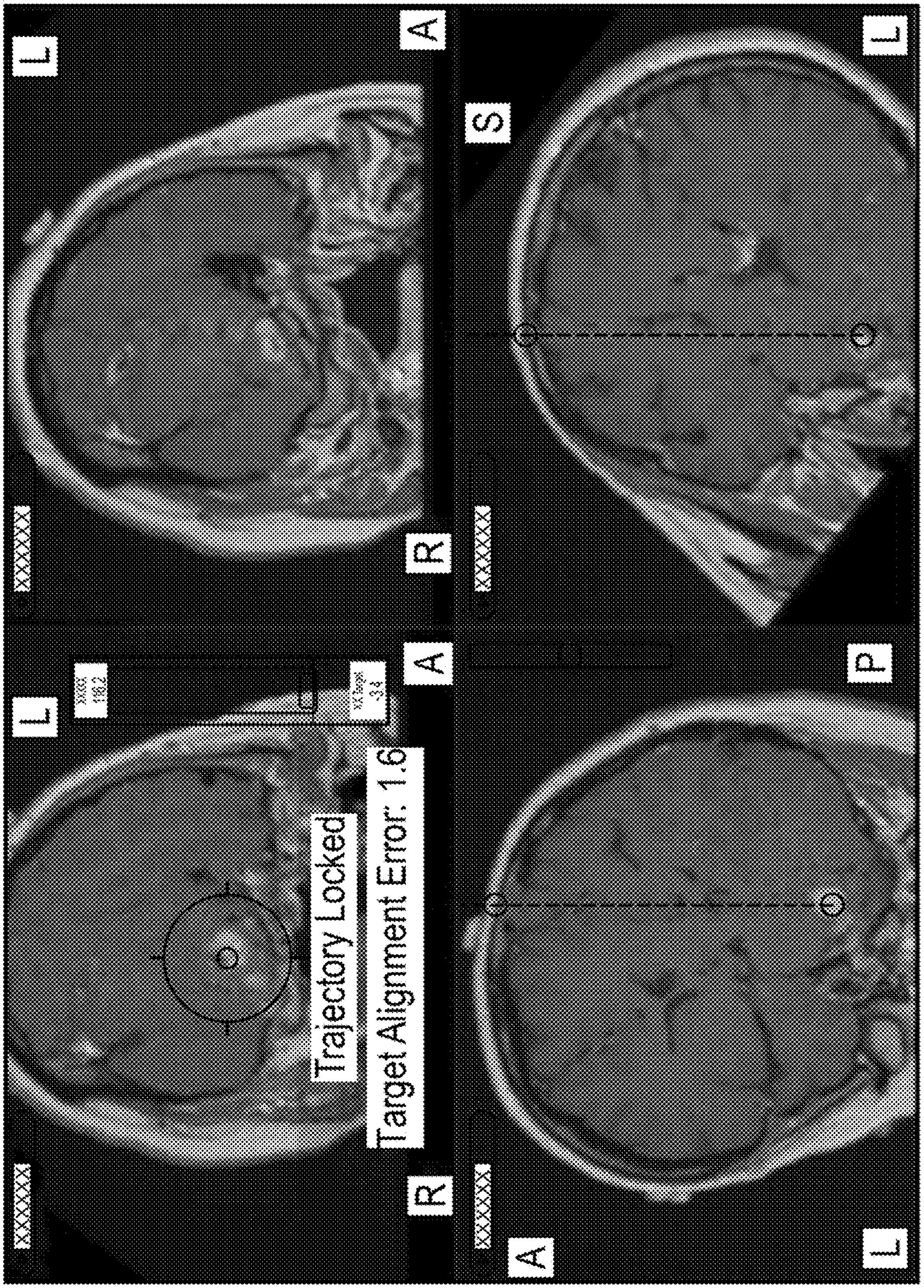


FIG. 22A
(PRIOR ART)

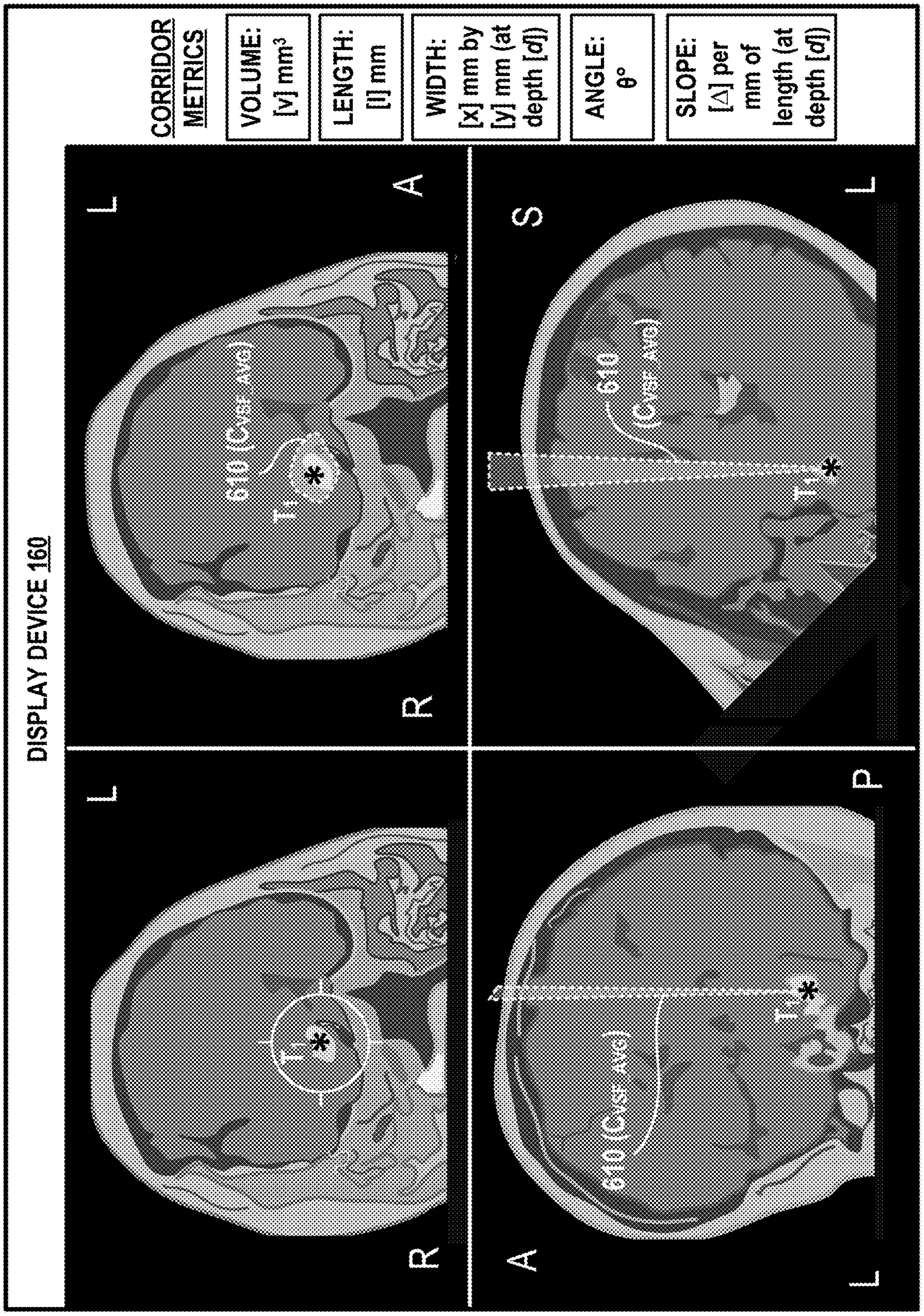

DISPLAY DEVICE 160
CORRIDOR METRICS
VOLUME: [v] mm³
LENGTH: [l] mm
WIDTH: [x] mm by [y] mm (at depth [d])
ANGLE: θ°
SLOPE: [Δ] per mm of length (at depth [d])
L
R
A
P
S
T1
610 (CVSF AVG)

FIG. 22B

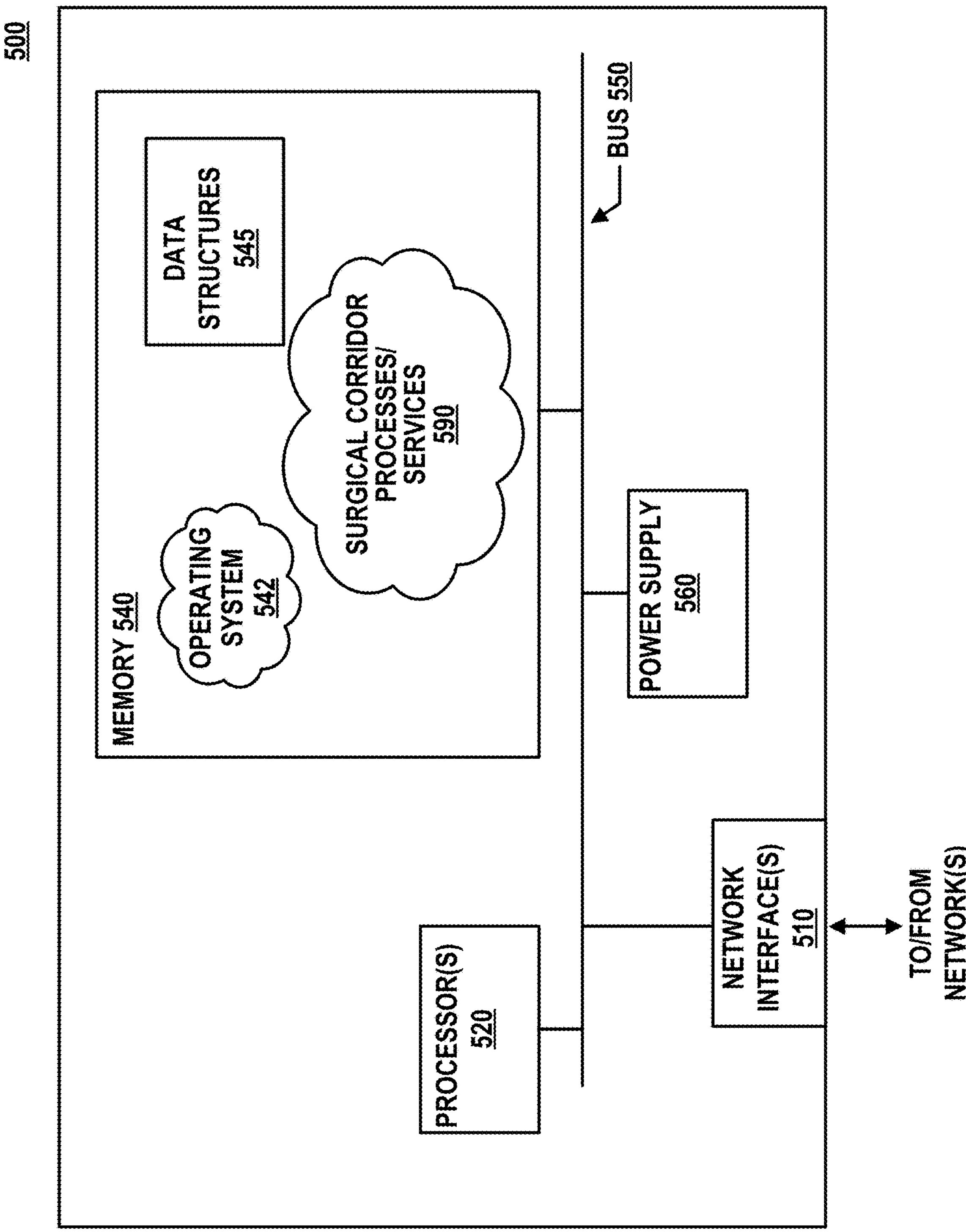

500
MEMORY 540
OPERATING SYSTEM 542
DATA STRUCTURES 545
SURGICAL CORRIDOR PROCESSES/ SERVICES 590
BUS 550
POWER SUPPLY 560
PROCESSOR(S) 520
NETWORK INTERFACE(S) 510
TO/FROM NETWORK(S)

FIG. 23

SYSTEMS AND METHODS FOR A SPATIAL QUANTITATIVE AND ANATOMICALLY ACCURATE SURGICAL CORRIDOR MODELING PLATFORM

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application is a continuation of U.S. patent application Ser. No. 17/738,273, filed May 6, 2022, which claims benefit of U.S. Provisional Patent Application Ser. No. 63/185,081 filed May 6, 2021, which are herein incorporated by reference in their entirety.

FIELD

[0002] The present disclosure generally relates to preoperative modeling, and in particular, to a system and associated method for generating an average surgical model for a surgical corridor from multiple sample sets.

BACKGROUND

[0003] Quantitative anatomy is the method by which neurosurgeons assess the surgical benefits and disadvantages of different surgical approaches using surgical technology. The purpose of studying quantitative anatomy is to improve the techniques and approaches used in neurosurgery or other related surgery disciplines. This process allows surgeons and related personnel to assess, plan and select the optimal intervention or surgical approach specific to the pathology, thereby aiming to improve surgical outcomes for patients. The ability to move and manipulate surgical instruments is an integral aspect of selecting an optimal surgical approach or comparing one surgical approach to another. This is especially relevant in neurosurgery, where surgical access through the cranium and into the deep areas of the brain is often restricted. Furthermore, in cases where the procedure is performed using an operating microscope for magnification, movement of surgical instruments to work on pathoanatomic structures may be in terms of millimetric distances.

[0004] Brain structure and topology, as well as other structures in the body, can vary significantly across a population with traits such as sex, age, and various conditions. For instance, the brain of a 75 year old male with dementia will be far different in size and shape from that of a 30 year old female without comorbidities, and thus a surgical approach to either individual will need to be examined differently. Thus, during training it is imperative that models be realistic representations of how to surgically access various structures.

[0005] It is with these observations in mind, among others, that various aspects of the present disclosure were conceived and developed.

BRIEF DESCRIPTION OF THE DRAWINGS

[0006] FIG. **1**A is a diagram showing a system for generating a model of a surgical corridor and FIG. **1**B is a diagram showing aspects of the system of FIG. **1**A for populating a database;

[0007] FIG. **2** is an illustration showing an example surgical corridor within a skull;

[0008] FIG. **3** is a flowchart showing a method for generating a model of a surgical corridor as performed by the system of FIG. **1**A;

[0009] FIG. **4** is a graphical representation showing measured data points including a first reference point, a second reference point, a target structure reference point, and a plurality of corridor points in a first 3D coordinate system according to the method of FIG. **3**;

[0010] FIG. **5** is a graphical representation showing the measured data points of FIG. **4** including the first reference point, the second reference point, the target structure reference point, and the plurality of corridor points translated to a second 3D coordinate system with the target structure reference point located at a center of the second 3D coordinate system;

[0011] FIG. **6** is a flowchart showing substeps of the method of FIG. **3** as illustrated in FIGS. **4** and **5**;

[0012] FIG. **7** is a graphical representation showing the measured data points and second 3D coordinate system of FIG. **5** including a centroid corridor line associated with the plurality of corridor points;

[0013] FIG. **8** is a graphical representation showing the measured data points and the second 3D coordinate system of FIG. **5** defining an average perpendicular plane perpendicular to the centroid corridor line of FIG. **7**;

[0014] FIG. **9** is a flowchart showing substeps of the method of FIG. **3** as illustrated in FIGS. **7** and **8**;

[0015] FIG. **10** is a graphical representation showing translation of the plurality of corridor points to the average perpendicular plane of FIG. **8**;

[0016] FIG. **11** is a graphical representation showing alignment of a first 2D coordinate system with translated corridor points defined on the average perpendicular plane of FIG. **10**;

[0017] FIG. **12** is a flowchart showing substeps of the method of FIG. **3** as illustrated in FIGS. **10** and **11**;

[0018] FIG. **13** is a graphical representation showing determination of a plurality of polynomials of spline curves that fit to the plurality of corridor points to determine a shape of a surgical corridor within the first 2D coordinate system of FIG. **11**;

[0019] FIG. **14** is a graphical representation showing generation of additional data points along a plurality of radial division lines that fit to the spline curve of FIG. **13**;

[0020] FIG. **15** is a flowchart showing substeps of the method of FIG. **3** as illustrated in FIGS. **13** and **14**;

[0021] FIG. **16** is a graphical representation showing a sample 3D model representing an output of an average surgical corridor model of the system of FIG. **1**A;

[0022] FIG. **17** is a flowchart showing substeps of the method of FIG. **3** as illustrated in FIG. **16**;

[0023] FIGS. **18**A-**18**D are example images showing superposition of a model of the average surgical corridor on patient imaging using the system of FIG. **1**A;

[0024] FIG. **19** is a flowchart showing generation of the model of the average surgical corridor by the system of FIG. **1**A based on user-provided selections;

[0025] FIG. **20** is a diagram showing a database layout for the system of FIG. **1**A;

[0026] FIG. **21** is a simplified diagram showing integration of the system of FIG. **1**A with a surgical assistance environment;

[0027] FIGS. **22**A and **22**B are a pair of images respectively showing an output of a previous image-based surgical planning system and an example output of an image-based surgical planning system of FIG. **21** that incorporates the model of FIG. **18**A into the surgical planning environment; and

[0028] FIG. **23** is a simplified diagram showing an exemplary computing system for implementation of the system of FIG. **1**A.

[0029] Corresponding reference characters indicate corresponding elements among the view of the drawings. The headings used in the figures do not limit the scope of the claims.

DETAILED DESCRIPTION

[0030] Various embodiments of a computer-implemented system and associated method for determining and displaying a model for an average surgical corridor from multiple sample sets are disclosed herein. The system includes a large database of cadaveric measurements that includes information used in creating **3**D models of surgical corridors specific to different approaches, maneuvers and structures. To achieve a predictive model for a combination of side, approach, maneuver, and structure, measurements related to this combination can be selected from the database. Using different anatomical information attached to each cadaveric measurement, such as age, sex, cranial volume and parenchymal volume obtained from preclinical imaging (magnetic resonance, computed tomography, ultrasound, or any other imaging modality that can produce volumetric imaging data), a subset of a plurality of datasets can be chosen based on the age, sex, cranial volume, parenchymal and other patient-specific anatomy. Selected datasets are then combined to produce an "average" 3D surgical corridor, which is spatially accurate and spatially oriented and can be superimposed on imaging of the patient's anatomy to produce a predictive 3D surgical corridor for use pre-operatively or intraoperatively.

[0031] While one cannot comprehensively quantitatively or qualitatively estimate the affect a lesion has on the intracranial space, or the amount of potential space garnered specific to an approach, the present system allows use of anatomical parameters to refine analysis. CT and MRI, or another imaging modality, can assess the volume of brain parenchyma as well as the volume of the intracranial compartment, i.e. the skull. In this database, the acquired imaging data set allows the measurement of the volume of the intracranial parenchyma, the total intracranial volume and segment the cranium into different compartments (supratentorial, infratentorial etc.). Comparing this with collected cadaveric quantitative data and demographics, the patient's anatomical and radiographic volumetric parameters can be used to predict the volume of surgical freedom (VSF) of surgical target structures relevant to the surgical corridor(s) specific to the patient's cranial anatomy.

[0032] In particular, the system is operable for accepting data including a plurality of 3-dimensional locations of various points within a body. Data can be for a plurality of bodies across a plurality of datasets to identify an "average" surgical corridor among the bodies of a selected dataset. This can prove useful when generating specialized "averages" for surgical and anatomical study or planning, such as for an average surgical corridor for a cohort defined alone or singly, or for instance in combination with imaging, image-guided surgical navigation systems, or robotic surgical systems where delineation of the surgical corridor and/or surgical access limitations are defined (e.g., "no fly zones"). Current image-guided surgical systems use a single line to represent the trajectory from the point of entry on the skull to the target of surgical interest. In contrast, the present disclosure describes creation of a model of an average surgical corridor that can be incorporated into an image-guided surgical system such that the trajectory of the approach is not represented by a single line, but is instead presented to the operator as a three dimensional corridor. This average surgical corridor can be used in real time as part of the image guided surgical system to visualize the expected freedom of movement of surgical instruments available to the surgeon.

[0033] Referring to FIGS. **1**A-**5**, a surgical corridor modeling system **100** (hereinafter, system **100**) provides a computing device **101** that implements various methods for generating a model of an average surgical corridor based on anatomical coordinate data. The computing device **101** includes a plurality of modules, collectively "average surgical corridor processes/services" **120**, that communicate with a database **130** that includes anatomical coordinate data for a plurality of datasets, where each dataset corresponds to a respective specimen of a plurality of specimens. In particular, the database **130** receives and stores 3-dimensional positional data for a plurality of datasets; each dataset of the plurality of datasets including a set of measured data points for various reference points within a structure of the body, and each dataset of the plurality of datasets corresponds to a respective specimen of a plurality of specimens. In one embodiment, each dataset includes positional data from various points around a skull and a target structure within the brain on cadaveric specimens. The system **100** combines an anatomical volumetric database such as database **130** with the average surgical corridor processes/services" **120** that perform volumetric imaging analysis to produce a model that can represent a patient's expected anatomical and radiographic volumetric parameters and thus predict a volume of surgical freedom to reach surgical target structures of the respective surgical corridors specific to the patient's cranial anatomy, resulting in quantitative and visual information for pre-operative and intra-operative planning. The system further includes a user interface **140** in communication with a display device **160** for entering information and for viewing the model and patient imaging. In some embodiments, the user interface **140** can be viewed in a web browser.

[0034] In some embodiments, the average surgical corridor processes/services **120** receives data from the user interface **140**, which can include one or more sets of measured data points for populating the database **130** and can also include selection information indicative of one or more selections received from a user to generate an "expected" surgical corridor based on the selection information. For instance, the average surgical corridor processes/services **120** can receive selection information from a practitioner through the user interface **140** such as a type of procedure to be performed on a living patient, an age range, a surgical approach, a head side, and/or a gender of the patient. The average surgical corridor processes/services **120** can then search the database **130** to identify a plurality of selected datasets which are a subset of the plurality of datasets that correspond to the selection information. Following identification of the plurality of selected datasets, the average surgical corridor processes/services **120** can determine an average surgical corridor and generate a model of the average surgical corridor based on sets of measured data points present in the plurality of selected datasets, and can further calculate a plurality of surgical corridor metrics including normalized volume based on the average surgical corridor. The average surgical corridor processes/services **120** can then communicate with the user interface **140** to display the model of the expected surgical corridor superimposed over patient imaging at the display device **160**. This process is elaborated on in further detail herein with reference to FIGS. **18A-19**.

[0035] As shown, the average surgical corridor processes/services **120** includes a user management module **121** for validating a user and maintaining user profiles. Further, the average surgical corridor processes/services **120** includes a data import/export module **122** in communication with the user interface **140** for importing datasets into the database **130**, and an input validation module **123** for ensuring that imported data is properly formatted upon entry into the database **130**. The average surgical corridor processes/services **120** provides an average surgical corridor modeling tool **124** that models the average surgical corridor based on the plurality of selected datasets of the plurality of datasets, the average surgical corridor modeling tool **124** retrieves based on the selections received through the user interface **140**. The average surgical corridor processes/services **120** can also include a metric calculator **125** that calculates various metrics related to the datasets and the modeled average surgical corridor.

[0036] The data import/export module **122** can also export data from the metric calculator **125** and the average surgical corridor modeling tool **124**, which can include a model of the average surgical corridor. In some embodiments, the user interface **140** displays the model of the average surgical corridor superimposed over patient imaging at the display device **160** as will be discussed in further detail herein with reference to FIGS. **18A-18D**.

Database Population

[0037] As shown specifically in FIGS. **1B** and **2**, to populate the set of measured data points for each dataset within the database **130**, **3**-D positional coordinates of two reference points R_1 and R_2 must be recorded for each dataset of the plurality of datasets. In some embodiments, the system **100** can include a dataset recordation module **110** on the computing device **101** in electrical communication with a probe **10** that populates the database **130** with a set of measured data points for each respective dataset of the plurality of datasets, which can be further validated with input validation module **123** that ensures proper formatting of the extracted data points. In one particular embodiment involving cranial surgery, for each dataset corresponding to a respective "head" of a plurality of heads, the system **100** extracts positions of a first reference point R_1 at the glabella (right between the eyebrows) and a second reference point R_2 at the lateral canthus (lateral edge of the eyelid) by the probe **10**. Further, the system **100** measures positional coordinates of a target structure T_1 within the body. To enable the system **100** to measure the positional coordinates, a practitioner can place the probe **10** with a distal end **12** of the probe **10** at the target structure T_1. Using the probe **10**, the system **100** captures a plurality of original corridor points C_1-C_m at the skull around a surgical corridor such that the distal end **12** of the probe **10** is still on the target structure T_1 and the plurality of original corridor points C_1-C_m are at the extrema of the surgical corridor. As such, the set of measured data points obtained by the system **100** for each respective dataset of the plurality of datasets can include positions of the first reference point R_1, the second reference point R_2, the target structure T_1, and the plurality of original corridor points C_1-C_m. It should be noted that while the discussion herein pertains to target structures within the brain and the plurality of original corridor points are on the skull in the context of cranial surgery, various other bodily structures are contemplated.

[0038] Cadaveric measurement data considers the movement of structures during a specific surgical approach, as well as the actions or maneuvers of a surgeon while they are operating. Combining this with patient imaging could provide a more detailed pre-operative picture, which provides the surgeon not only with an anatomical insight specific to the patient and to access the pathology or surgical situation, but also the likely potential space that can be garnered during a specific approach, and the areas and structures that are most likely to be impacted during the approach. This allows for more informed pre-operative approach selection or planning such as with surgical planning systems that may or may not incorporate image guidance or robotically-based surgical systems.

[0039] Intraoperatively, the model of the average surgical corridor can be aligned to the patient's imaging dataset and displayed at the display device **160** to produce a graphical guide to safe zones during intra-operative manipulation. This could be used as a visual guide for the surgeon to inform the approach in real time. In some embodiments, the system **100** can flag instances of a surgical instrument moving outside the surgical corridor or safe zone and display an alert at the display device **160** or another suitable output device to inform a practitioner of such an event.

Measurement Data

[0040] With reference to FIGS. **2-4**, the system **100** can obtain the set of measured data points including 3D positional coordinate data of three reference points for all datasets, each dataset corresponding to one specimen of a plurality of specimens and including 3-D coordinates for the following reference points:

[0041] Structure of interest (STS) T_1

[0042] First reference point R_1

[0043] Second reference point R_2

[0044] In one embodiment, the first reference point R_1 is selected to be the glabella, which is located at a midpoint between the eyebrows and above the nose. The second reference point R_2 is selected to be the lateral canthus, which is located at a lateral intersection of the upper eyelid and the lower eyelid.

[0045] Reference points T_1, R_1 and R_2 are used to orient the model in 3D space and in relation to other models.

[0046] The set of measured data points of each individual dataset of the plurality of datasets further includes the plurality of original corridor points C_1-C_m where the plurality of original corridor points C_1-C_m are points in 3D space, measured towards a proximal end **14** of the probe **10** with the distal end **12** on the target structure T_1, and the probe **10** placed at the extrema of maneuverability in the surgical corridor. Any number of points greater than 3 can be used for the surgical corridor modeling system **100**, and the greater the number of points, the more accurate the model will be. One example implementation of this methodology uses m=8 data points C_1-C_8.

[0047] The system **100** can combine sets of measurement data from plurality of selected datasets to produce a model of an "average" 3D surgical corridor, which is spatially accurate and spatially oriented and can be superimposed over imaging of the patient's anatomy to produce a predicted 3D surgical corridor for use pre-operatively or intraoperatively. Orientation points included with cadaveric data can be used to orient the surgical corridor in 3D space, and can allow the superimposition of the model onto the patient's imaging dataset by aligning a small number of these orientation points with the corresponding anatomical features of the patient's imaging. Determination and modeling of the volume of surgical freedom allows the means to produce anatomically and spatially accurate representations of the surgical corridor with respect to the patient's imaging parameters. Further, the model of the surgical corridor can be used to aid surgical planning and can be incorporated into image guided surgical planning systems, stereotactic navigation systems, and/or robotic surgical systems.

[0048] It should be noted that any means of 3D volume imaging can be used to generate the dataset and/or to generate patient imaging dataset(s) for superposition of a modeled surgical corridor onto the imaging. Such an imaging dataset can become incorporated as the basis of image guidance or image control for surgical planning systems and/or robotic surgical systems. While the surgical corridor modeling system **100** can use traditional 3D medical imaging such as CT or MRI, the surgical corridor modeling system **100** can also accept data from any medical imaging system, device, instrument, or tool that produces or can be altered to produce a 3D volumetric imaging dataset. For instance, the system **100** can include a 2D dataset that is altered or supplemented to become a 3D volumetric dataset. In some embodiments, the surgical corridor modeling system **100** can be used to superimpose a model of an average surgical corridor on patient imaging at an appropriate location relative to a target structure.

Average Surgical Corridor Derivation

Overview

[0049] Referring to FIG. **3** and as further illustrated in FIGS. **4-16**, a method **200** is shown for generating an average surgical corridor C_{VSF_AVG} by the system **100** using sets of measured data points taken from the plurality of selected datasets of the plurality of datasets, each respective dataset of the plurality of datasets corresponding to one specimen of a plurality of specimens. At block **210** of method **200**, the process of which is elaborated on in FIGS. **4-6**, the system **100** translates the set of measured data points for each selected dataset including 3D positional coordinate data from a first 3D coordinate system to a standardized second 3D coordinate system, including the first reference point R_1, the second reference point R_2, the target structure reference point T_1, and the plurality of original corridor points C_1-C_m. The second 3D coordinate system is oriented as shown in FIG. **5**, however it should be noted that the orientation of the second 3D coordinate system is not limited to this configuration and other orientations of the second 3D coordinate system are also contemplated. At block **220**, the process of which is elaborated on in FIGS. **7-9**, the system **100** determines a centroid line L_C for each selected dataset of the plurality of selected datasets based on the plurality of original corridor points C_1-C_m relative to the target structure T_1, and the system **100** further determines an average central axis line L_{AVG} for all of the plurality of selected datasets by averaging together each centroid line L_C of each selected dataset of the plurality of selected datasets. Using average central axis line L_{AVG}, the system **100** determines an average perpendicular plane P_{AVG} perpendicular to the average central axis line L_{AVG}. In some embodiments, the average perpendicular plane P_{AVG} can be represented at a fixed distance outside of the body to enable projection of the surgical corridor shape to any distance outside the body. At block **230**, the process of which is elaborated on in FIGS. **10-12**, the system **100** translates the original corridor points C_1-C_m for each selected dataset of the plurality of selected datasets to the average perpendicular plane P_{AVG} to provide a plurality of translated corridor points C_1'-C_m' for each dataset on a first 2D coordinate system. This allows the system **100** to directly compare data between each respective selected dataset of the plurality of selected datasets since each corridor point is now on a standardized coordinate system. At block **240**, the process of which is elaborated on in FIGS. **13-15**, the system **100** generates a shape of a surgical corridor C_{VSF} for each selected dataset of the plurality of selected datasets by fitting a spline curve S_P to the translated corridor points C_1'-C_m'. The system **100** generates additional data points D_1-D_N equidistantly along the spline curve S_P to further fill in the surgical corridor C_{VSF}. At block **250**, further in FIG. **16**, the system **100** generates an average surgical corridor C_{VSF_AVG} based on each outer shape of the surgical corridor C_{VSF} for each respective selected dataset of the plurality of selected datasets collectively described by the translated corridor points C_1'-C_m', the additional data points D_1-D_N and target structure T_1 for each respective dataset. The system **100** can translate the average surgical corridor C_{VSF_AVG} to a 3D coordinate system. At block **260**, the system **100** displays a model of the average surgical corridor C_{VSF_AVG} Superimposed on patient imaging at the appropriate location relative to the target structure and the average plane as shown in FIGS. **18**A-**18**D.

Translation of Data in 3D Space

[0050] Referring to FIGS. **3-6**, the first step to determine the average surgical corridor is illustrated in block **210** (FIG. **6**) of method **200**. In a first block **212** of block **210**, the system **100** obtains the reference points R_1, R_2 and T_1, as well as original corridor points C_1-C_m for each selected dataset of the plurality of selected datasets. At a second block **214** of block **210**, the system **100** translates the reference points R_1, R_2 and T_1, as well as original corridor points C_1-C_m in 3D space from a first 3D coordinate system to a second 3D coordinate system. An example first 3D coordinate system is illustrated in FIG. **4**; translated points are shown in FIG. **5** in the second 3D coordinate system. The purpose of the translation is such that all of the plurality of selected datasets can be aligned in 3D space.

[0051] The system **100** places the target structure reference point T_1 at the origin of the second 3D coordinate system. Further, the system **100** identifies a reference point R_3 as a point midway on a line L_R between the first reference point R_1 and the second reference point R_2. The system **100** "draws" a line joining reference midpoint R_3 to the target structure reference point T_1 along the X-axis of the second

3D coordinate system, and places the first and second reference points R_1 and R_2 on an XY plane of the second 3D coordinate system such that the XY plane intersects all three reference points R_1, R_2 and R_3.

[0052] To maintain consistency between all measured datasets, the y coordinate of the first reference point R_1 can always be negative, and the y coordinate of the second reference point R_2 can always be positive, thus ensuring the model is aligned consistently. It should be noted that for other structures of the body, reference points R_1 and R_2 can be selected at different landmarks and are not limited to the glabella and lateral canthus; however the landmarks of selected reference points do need to be consistent across all datasets.

[0053] Once the system **100** establishes the reference points R_1, R_2 and R_3 of the second 3D coordinate system as in block **212**, the system **100** translates the reference points and the original corridor points of each dataset of the plurality of selected datasets to the second 3D coordinate system in block **214**.

Calculation of Cone Central Axis Line for Each Dataset

[0054] Referring to FIGS. **3** and **7-9**, at sub-block **222** of block **220**, the system **100** identifies a centroid point C_{SET} of the original corridor points C_1-C_m for each selected dataset of the plurality of selected datasets by separately averaging x, y and z coordinates of all the original corridor points C_1-C_m for the dataset. The system **100** identifies a central axis line L_C of a cone shape by finding a difference vector between the target structure reference point T_1 and the centroid point C_{SET} of the original corridor points C_1-C_m, where the cone shape is representative of the surgical corridor.

Calculation of an Average Perpendicular Plane

[0055] Referring to FIGS. **3** and **7-9**, at sub-blocks **224** and **226** of block **220**, the system **100** determines an average central axis line L_{AVG} having an average centroid point C_{AVG} across the plurality of selected datasets by averaging x, y and z coefficients for a plurality of central axis lines L_C respectively associated with each centroid point C_{SET} of each respective selected dataset of the plurality of selected datasets. The system **100** can then characterize an average perpendicular plane P_{AVG} for the plurality of selected datasets as a plane for which the average central axis L_{AVG} is the normal vector. The absolute position of the average perpendicular plane P_{AVG} in 3D space is reasonably arbitrary, but the average surgical returned is more useful if the model extends from the target structure reference point T_1 to the outside of the skull in all cases, so a fixed length can be selected to ensure this; for example 200 mm. With a fixed distance between the target structure reference point T_1 and the average perpendicular plane P_{AVG}, the average perpendicular plane P_{AVG} can be fully defined in 3D space.

Translation of the Coordinate Data From Each Dataset to the Average Perpendicular Plane

[0056] Referring to FIGS. **3** and **10-12**, at sub-block **232** of block **230**, the system **100** determines a plurality of vectors between the target structure reference point T_1 and each original corridor point C_1-C_m of each dataset, and calculates the intersection of these vectors with the average perpendicular plane P_{AVG} to translate each original corridor point C_1-C_m to the average perpendicular plane P_{AVG}. These intersection points are the new translated corridor points C_1'-C_m' for each respective selected dataset of the plurality of selected datasets after translation onto the average perpendicular plane P_{AVG} and extending along the same lines between the target structure reference point T_1 and the original corridor points C_1-C_m.

Translation to a 2D Coordinate System

[0057] Referring to FIGS. **3** and **10-12**, at sub-block **234** of block **230**, once the data points have been translated on to the average perpendicular plane P_{AVG} which is standardized, the system **100** can define a first 2D coordinate system on the average perpendicular plane P_{AVG}. The orientation of this 2D coordinate system must be very carefully considered and must be consistent for all data points. There are 3 orientation options that the system **100** can use for orienting the axes:

[0058] 1. Orient the X-axis of the new 2D coordinate system along the projection of the line joining the target structure reference point T_1 and the first reference point R_1.

[0059] 2. Orient the X-axis of the new 2D coordinate system along the projection of the line joining the target structure reference point T_1 and the second reference point R_2.

[0060] 3. Orient the X-axis of the new 2D coordinate system along the projection of the line joining the target structure reference point T_1 and the midpoint R_3 between the first reference point R_1 and the second reference point R_2. This option will most likely prove to be the best option, as the variation in distance between the first reference point R_1 and the second reference point R_2 will be split evenly between the two sides. In the other two cases, the variation in distance will offset all of the measured data points in one direction.

[0061] When the X-axis orientation has been fixed on the average perpendicular plane P_{AVG}, the system **100** can easily determine the Y-axis at right angles to the X-axis. If the same calculation method is applied consistently by the system **100**, the orientation of the Y-axis will be consistent on the 2D plane. The system **100** can then convert 3D coordinate data of the translated corridor points C_1'-C_m' for a selected dataset of the plurality of selected datasets to a 2D coordinate system on the average perpendicular plane P_{AVG}. It should be noted that although the average perpendicular plane P_{AVG} is used in this method as the plane on which to create the 2D coordinate system, many other choices of planes could be used. One such example would be to use a plane parallel but offset to the reference plane.

Calculation of the Piecewise Polynomials of Spline Curves for Each Dataset

[0062] Referring to FIGS. **3** and **13-15**, at sub-block **242** of block **240**, the system **100** approximates the shape of the surgical corridor for each selected dataset of the plurality of selected datasets using a piecewise spline curve S_P for each individual dataset. The system **100** generates the piecewise spline curve S_P using the translated data points C_1'-C_m' (after translation to the 2D coordinate system) as control points for the piecewise spline curve S_P. The system **100** can define a plurality of respective spline curve sections S_1-S_m of the piecewise spline curve S_P using separate 3rd degree polynomials. The system **100** can determine the equations for each polynomial making up the spline curve S_P using the following constraints:

[0063] The piecewise spline curve S_P intersects all data points C_1'-C_m'.

[0064] A spline curve section Sm between each two points C_m', C_{m-1}' is governed by a separate cubic polynomial.

[0065] For adjacent spline curve sections, the slope of the spline curve sections are the same where the spline curve sections meet at the data points (e.g., first derivatives of the two polynomials are equal).

[0066] For adjacent spline curve sections, the curvature is the same where the spline curve sections meet (e.g., second derivatives of the polynomials are equal).

Calculation of Radial Intersection Points

[0067] Referring to FIGS. **3** and **13**-**15**, at sub-block **244** of block **240**, the system **100** draws radial reference lines V_1-V_N at fixed angles from the centroid C_{SET} of the 2D points of each individual dataset, which also corresponds with a relative XY position of the target structure T_1. At sub-block **246** of block **240**, to calculate an average surgical corridor shape, the system **100** defines a new, larger set of data points D_1-D_N along fixed references along the piecewise spline curve S_P for each individual dataset. The fixed references being used are radial reference lines V_1-V_N. The points of intersection between the reference radial lines V_1-V_N and the cubic polynomial of the piecewise spline curve S_P constitute the new set of data points D_1-D_N representing the shape of the surgical corridor on the 2D plane. In particular, the system **100** defines an intersection point D_u where $u \in \{1, \ldots, N\}$, where the radial reference line V_u intersects with the piecewise spline curve S_P. The polynomial has a check on the result to ensure that the correct polynomial for spline curve section S_t where $t \in \{1, \ldots, m\}$ of the spline curve S_P is being used. After the intersection point D_u has been calculated, the system **100** checks to ensure that the x and y values of the new coordinate D_u fall between the x and y values of the two data points C_t' and C_r' where $t,r \in \{1, \ldots, m\}$ at the limits of the polynomial being calculated. If the new intersection point D_u is outside this range, the intersection D_u with the radial reference line V_u in question is calculated on the next spline curve section of the spline curve S_P.

[0068] The result of these calculations is that for each radial reference line V_u, there will be one intersection point D_u associated with it in each dataset.

Calculation of Average Surgical Corridor on 2D Plane

[0069] Referring to FIGS. **3**, **16** and **17**, at block **250**, the new set of data points D_1-D_N for each dataset has been determined from a fixed reference C_{SET} which is common to all datasets, the points are directly comparable. At sub-block **252** of block **240**, to determine the average surgical corridor C_{VSF_AVG} in the 2D coordinate system, for each respective radial reference line V_u, the system **100** calculates the averages of the intersection point D_u associated with the radial line V_u on all datasets. This gives a single 2D reference point D_u for each radial reference line V_u, and together, these 2D points collectively define the outline of the average surgical corridor C_{VSF_AVG} that is an average surgical corridor across the plurality of datasets.

Translation of Average Points Back to 3D Space

[0070] Referring to block **254** of block **250** of FIG. **17**, the target of the method **200** is to produce a model of the average surgical corridor from the selected datasets, so when the data points comprising the average surgical corridor are calculated, they must then be translated back to the global 3D coordinate system. The relationship between the 2D and 3D coordinate systems have been established from the earlier translation in the other direction.

Result

[0071] The result of the method **200** is to produce a model **610** of the average surgical corridor C_{VSF_AVG}, shown in FIGS. **16**-**18**D. The model **610** includes at least 3 reference points, the target structure reference point T_1, the first reference point R_1 and the second reference point R_2. In the embodiments of FIGS. **16** and **18**A, the model **610** can be a 3D model, and can be aligned over patient imaging and displayed at the display device **160**. In some embodiments, patient imaging can be in the form of a 3D patient model **60**, which can be created by assembling a plurality of cross-sectional image "slices" into a 3D model. In the embodiment of FIGS. **18**B-**18**D, patient imaging can be represented at the display device **160** as one or more cross-sectional images (collectively, imaging "slices" **62**) such as a T**1**-weighted imaging "slice" **62**A, a T**2**-weighted imaging "slice" **62**B, and a PD-weighted imaging "slice" **62**C, with a corresponding "slice" **612** of the model **610** positioned where it belongs relative to the imaging "slices" **62** of the patient imaging. With these reference points, the system **100** can align the model **610** with patient imaging in the following ways:

[0072] 1) Move the model **610** with respect to the patient imaging such that the surgical target structure reference point T_1 of the model **610** (e.g., the apex of the cone shape) is coincident with the surgical target structure in patient imaging.

[0073] 2) Rotate the model **610** to achieve the best alignment of the first reference point R_1 and the second reference point R_2 associated with the model **610** with their corresponding positions in patient imaging.

[0074] In this way, at block **260** of FIG. **3**, the system **100** can superimpose the model **610** of the average surgical corridor on patient imaging to produce a combined model of the patient's imaging dataset(s) and an expected surgical corridor.

Method of Use

[0075] For a user to interact with the system **100** to generate and use the model of the average surgical corridor, the database **130** that provides the set of measured data points must be available to the user through the user interface **140**. FIG. **19** illustrates an overall method **300** by which the system **100**, illustrated in FIG. **1**A, provides an average surgical corridor to the user.

[0076] 1) At block **310** of method **300**, the system **100** receives a query through the user interface **140** that indicates the following procedural information regarding a surgical procedure to be performed:

[0077] Surgical target structure

[0078] Surgical Approach.

[0079] Head Side

[0080] Maneuver

[0081] Laterality

[0082] Visualization Method

[0083] 2) At block **320** of method **300**, the system **100** receives a combination (some or all) of the following patient-specific information regarding the surgical procedure to be performed through the user interface **140**:

[0084] Age (number and/or range)

[0085] Sex

[0086] Pathology

[0087] Neuroimaging volumetric (computed tomography or magnetic resonance imaging)/anatomical parameters for example:

[0088] Total Intracranial volume

[0089] Parenchymal volume

[0090] (i) Supratentorial volume

[0091] (ii) Intratentorial volume

[0092] The patient-specific information and procedural information is used by the system **100** to identify one or more similar datasets of the plurality of datasets within the database **130**. For instance, a practitioner can enter a query for a patient into the user interface **140** that includes procedural information and patient-specific information so that the system **100** can generate the model of the average surgical corridor (such as model **610** of FIGS. **18A-18D**) based on a plurality of selected datasets that fall within an appropriate range of similarity to the patient.

[0093] 3) At block **330** of method **300**, the system **100** queries the database **130** based on the procedural information and the patient-specific information to identify a plurality of selected datasets of a plurality of datasets stored within the database **130**. At block **340** of method **300**, the system **100** retrieves the plurality of selected datasets from the database **130**.

[0094] The system **100** receives a selection of a range or tolerance for each of the patient specific parameters, and searches the database for all datasets which fall within the specified range/tolerance of the patient information.

[0095] The system **100** can have specific tolerances set for each patient specific parameter, and the system **100** searches for all entries within the tolerances.

[0096] The system **100** can have a specified minimum number of entries required to determine the average surgical corridor, and widens or tightens the tolerances to retrieve the specified number of entries from the database. In this way, for a set of parameters for which there exists a lot of data, the entries returned can be within a very tight tolerance of the patient specific parameters, but if there is a scarcity of data, tolerances of the system **100** can be expanded to ensure a minimum number of entries are used to determine the average surgical corridor.

[0097] In some embodiments, a practitioner can review the plurality of selected datasets to accept or reject one or more of the selected datasets of the plurality of selected datasets.

[0098] 4) At block **350** of method **300**, the system **100** calculates the average surgical corridor based on the surgical corridors belonging to the plurality of selected datasets (e.g., using method **200** described herein). At block **360** of method **300**, the system **100** returns various metrics including the average normalized volume of the surgical corridors. At block **370** of method **300**, the system **100** generates a 3D model such as model **610** of the average surgical corridor.

[0099] 5) At block **380**, the system **100** superimposes the 3D model over patient imaging and aligns the model such that the surgical target structure reference point T_1 of the 3D model is coincident with the surgical target structure in the patient imaging, the first reference point of the 3D model is aligned as closely as possible with a corresponding position in the patient imaging, and the second reference point of the 3D model is aligned as closely as possible with a corresponding position in the patient imaging. At block **390**, the system **100** displays, at the display device **160**, the 3D model of the average surgical corridor with respect to patient imaging. An example of this is shown in FIG. **18**A, where the model **610** is a 3D model superimposed over a 3D model **60** representative of patient imaging. In FIGS. **18**B-**18**D, the system **100** can display the model **610** as a slice **612** superimposed over cross-sectional imaging "slices" **62** representative of patient imaging.

[0100] In some embodiments, components of surgical corridor modeling system **100** can be at least partially developed as a web application, designed for cloud hosting, and/or accessible to registered users from any web browser.

Database Model

[0101] FIG. **20** illustrates an example database **130** for organizing data within the plurality of datasets for operation of the system **100**. To calculate an average surgical corridor model C_{VSF_AVG}, the database **130** needs to be adequately labeled. For a particular embodiment, each dataset in the database **130** requires the following information:

[0102] Surgical target structure

[0103] Surgical Approach.

[0104] Head Side

[0105] Unique identifier for head (head number)

[0106] In addition, the following data should also be used to distinguish between different datasets:

[0107] Manoeuver(s) used during approach

[0108] Laterality

[0109] Visualization method (endoscope or microscope)

[0110] The following information is required for each head, as identified by a head number:

[0111] Age

[0112] Sex

[0113] Total Intracranial Volume

[0114] Parenchymal Volume

[0115] Supratentorial volume

[0116] Infratentorial volume

[0117] Surgical System Integration

[0118] FIG. **21** illustrates an example surgical assistance environment **400** that incorporates the surgical corridor modeling system **100** to provide practitioners with helpful volumetric information about a surgical corridor during a surgical case. As shown, the surgical assistance environment **400** can incorporate the surgical corridor modeling system **100** with an image-guided surgical planning system **410** for preoperative planning and can further include a stereotactic navigation system **420** for intra-operative navigation. In the example shown, the surgical corridor modeling system **100** can receive patient imaging from an imaging system **50**, such as a magnetic resonance imaging system or another imaging modality, and can superimpose the model **610** of the average surgical corridor C_{VSF_AVG} over patient imaging. The model **610** can be displayed at display device **160** along with patient imaging. The surgical corridor modeling system **100** can further communicate the model **610** of the average surgical corridor C_{VSF_AVG} to the image-guided surgical planning system **410** for pre-operative planning and stereotactic registration. With reference to FIG. **22**A, current image-guided surgical planning technologies show trajectories by simple lines on the display that point to the surgical target structure, sometimes including metrics such as distances and lengths. In contrast, with reference to FIG. **22**B, the image-guided surgical planning system **410** can display the model **610** indicative of the average surgical corridor over patient imaging at the display device **160** that provides a volume or an otherwise more informative volumetric trajectory that renders a surgical approach shape and/or volume of the surgical workspace, rather than simple lines. Further, in some embodiments, the image-guided surgical planning system **410** can display various corridor metrics related to the model **610** at the display device **160** to provide quantitative information to practitioners such as allowable working volume, approach angle, etc. In the example shown, corridor metrics can include but are not limited to a total volume, a total length, an expected corridor width (which can vary by depth below a surface), an approach angle, and/or a slope of the corridor (e.g., how sharply the corridor narrows as the corridor approaches the surgical target structure, which can vary by depth relative to the surface). In some embodiments, the image-guided surgical planning system **410** can incorporate assessments of a plurality of possible surgical corridors enabled by different surgical approaches to aid a practitioner in selecting an optimal surgical approach. For instance, the image-guided surgical planning system **410** can display a plurality of models such as model **610** superimposed over patient imaging along with corridor metrics for each model of the plurality of models. In some embodiments, the image-guided surgical planning system **410** can "highlight" approaches that have certain features, such as approaches having a maximal or minimal allowable working volume, a shortest corridor length, that avoid restricted areas, that have a reduced or minimal risk factor, etc. As such, incorporating the model **610** generated by the surgical corridor modeling system **100** with the image-guided surgical planning system **410** can enable a practitioner to make informed decisions when planning a surgical case.

[0119] In some embodiments, the image-guided surgical planning system **410** can communicate the model **610** along with anatomical navigation data to the stereotactic navigation system **420** for integration of the model **610** into the surgical workflow. During a surgical case, the stereotactic navigation system **420** can aid a practitioner with navigating the surgical workspace and can provide information related to positions and orientations of various surgical instruments and/or surgical tracking devices relative to the surgical workspace (such as an operating microscope or stereotactic markers). The stereotactic navigation system **420** can incorporate the model **610** into the surgical workflow by providing positions and orientations of instruments and other objects relative to the corridor outlined by the model **610**. For instance, the stereotactic navigation system **420** can register patient anatomy within a virtual space S, which can be a 3D virtual space indicative of the real surgical workspace. The stereotactic navigation system **420** can further define a volumetric range of a surgical corridor using the model **610** which can have a volumetric range $(\langle x_{m1}, x_{m2}\rangle, \langle y_{m1}, y_{m2}\rangle, \langle z_{m1}, z_{m2}\rangle) \in S$ within the virtual space S. Further, the stereotactic navigation system **420** can track positions of objects such as surgical instruments, stereotactic markers, or anatomical structures (e.g., generically, a position $P=(x_P, y_P, z_P) \in S$). By defining the volumetric range of the model **610** in the same virtual space as registered patient anatomy, and by defining the positions of various objects such as surgical instruments, stereotactic markers, or anatomical structures in the same virtual space, the stereotactic navigation system **420** can provide helpful navigational information to practitioners especially in terms of the allowable working volume of the average surgical corridor indicated by the model **610**. The stereotactic navigation system **420** can display this information including the model **610** and patient imaging at the display device **160**, the model **610** being indicative of a volumetric trajectory of a surgical approach. Further, in some embodiments, the stereotactic navigation system **420** can use the model **610** as provided by the surgical corridor modeling system **100** to initially estimate the surgical corridor and can update the model **610** as needed through observation of the surgical corridor in practice. In another aspect, the stereotactic navigation system **420** can monitor a position of a surgical instrument relative to the surgical corridor indicated by the model **610** to ensure that the surgical instrument does not exit the surgical corridor, and can provide one or more warnings, alerts or indications to a practitioner when the stereotactic navigation system **420** detects such an event.

[0120] Further, in some embodiments, the stereotactic navigation system **420** can communicate the model **610** to various surgical peripheral systems **450** such as a robotic surgical system **430** and/or an operating microscope **440**. In one example, the robotic surgical system **430** can receive the model **610** provided by the surgical corridor modeling system **100** as guidance for an expected surgical operating space, the model **610** being indicative of a volumetric trajectory of a surgical approach. In another example, the stereotactic navigation system **420** can receive video data of the surgical workspace from the operating microscope **440** and can display the video data from the operating microscope **440** at the display device **160** with reference to the model **610** indicative of the surgical corridor to further aid the practitioner when navigating the surgical workspace.

Computer-Implemented System

[0121] FIG. **23** is a schematic block diagram of an example device **500** that may be used with one or more embodiments described herein, e.g., as a component of surgical corridor modeling system **100** or as a component of surgical assistance environment **400**.

[0122] Device **500** includes one or more network interfaces **510** (e.g., wired, wireless, PLC, etc.), at least one processor **520**, and a memory **540** interconnected by a system bus **550**, as well as a power supply **560** (e.g., battery, plug-in, etc.).

[0123] Network interface(s) **510** include the mechanical, electrical, and signaling circuitry for communicating data over the communication links coupled to a communication network. Network interfaces **510** are configured to transmit and/or receive data using a variety of different communication protocols. As illustrated, the box representing network interfaces **510** is shown for simplicity, and it is appreciated that such interfaces may represent different types of network connections such as wireless and wired (physical) connections. Network interfaces **510** are shown separately from power supply **560**; however, it is appreciated that the interfaces that support PLC protocols may communicate through power supply **560** and/or may be an integral component coupled to power supply **560**.

[0124] Memory **540** comprises a plurality of storage locations that are addressable by processor **520** and network interfaces **510** for storing software programs and data structures associated with the embodiments described herein. In some embodiments, device **500** may have limited memory or no memory (e.g., no memory for storage other than for programs/processes operating on the device and associated caches).

[0125] Processor **520** comprises hardware elements or logic adapted to execute the software programs (e.g., instructions) and manipulate data structures **545**. An operating system **542**, portions of which are typically resident in memory **540** and executed by the processor, functionally organizes device **500** by, inter alia, invoking operations in support of software processes and/or services executing on the device. These software processes and/or services may comprise surgical corridor process/services **590**, described herein as average surgical corridor processes/services **120** and methods **200** and **300**. Note that while surgical corridor modeling process/services **590** is illustrated in centralized memory **540**, alternative embodiments provide for the process to be operated within the network interfaces **510**, such as a component of a MAC layer, and/or as part of a distributed computing network environment.

[0126] It will be apparent to those skilled in the art that other processor and memory types, including various computer-readable media, may be used to store and execute program instructions pertaining to the techniques described herein. Also, while the description illustrates various processes, it is expressly contemplated that various processes may be embodied as modules or engines configured to operate in accordance with the techniques herein (e.g., according to the functionality of a similar process). In this context, the term module and engine may be interchangeable. In general, the term module or engine refers to model or an organization of interrelated software components/functions. Further, while the surgical corridor modeling processes/services **590** is shown as a standalone process, those skilled in the art will appreciate that this process may be executed as a routine or module within other processes.

[0127] It should be understood from the foregoing that, while particular embodiments have been illustrated and described, various modifications can be made thereto without departing from the spirit and scope of the invention as will be apparent to those skilled in the art. Such changes and modifications are within the scope and teachings of this invention as defined in the claims appended hereto.

1. A system, comprising:

a processor in communication with a memory, the memory including instructions, which, when executed, cause the processor to:

receive, at a user interface in communication with the processor, a query including procedural information and patient-specific information regarding a procedure to be performed;

identify a plurality of selected datasets of a plurality of datasets stored within a database in communication with the processor based on the procedural information and the patient-specific information;

generate an average surgical corridor based on the plurality of selected datasets, wherein each selected dataset of the plurality of datasets includes a set of measured data points indicative of a shape of a surgical corridor;

generate a model indicative of the average surgical corridor; and

display, at a display device, the model indicative of the average surgical corridor with respect to patient imaging.

2. The system of claim **1**, wherein the memory includes instructions, which, when executed, further cause the processor to:

obtain the set of measured data points for a selected dataset of the plurality of selected datasets, the set of measured data points including a first reference point, a second reference point, a target structure reference point, and a plurality of corridor points, the set of measured data points defined within a first 3D coordinate system;

determine an average central axis line and an associated average perpendicular plane for the plurality of selected datasets based on the set of measured data points;

translate the plurality of corridor points associated with each respective selected dataset of the plurality of selected datasets to the average perpendicular plane to generate a plurality of translated corridor points associated with each respective selected dataset of the plurality of selected datasets;

generate a plurality of corridor intersection points that fit a spline curve for each respective selected dataset of the plurality of selected datasets, the spline curve being fit to the plurality of translated corridor points; and

generate the average surgical corridor based on a shape of a surgical corridor of each respective selected dataset of the plurality of selected datasets, the shape of the surgical corridor being determined for each respective selected dataset using the corridor intersection points and the target structure reference point.

3. The system of claim **2**, wherein the memory includes instructions, which, when executed, further cause the processor to:

translate, by the processor, the set of measured data points for each respective selected dataset of the plurality of selected datasets from the first 3D coordinate system to a standardized second 3D coordinate system.

4. The system of claim **2**, wherein the memory includes instructions, which, when executed, further cause the processor to:

determine, by the processor, a centroid line between the plurality of corridor points and the target structure for each respective selected dataset of the plurality of selected datasets;

determine, by the processor, an average central axis line between the centroid line associated with each respective selected dataset and the target structure; and determine, by the processor, the average perpendicular plane that is perpendicular to the average central axis line at a distance from the target structure.

5. The system of claim **4**, wherein the memory includes instructions, which, when executed, further cause the processor to:

record a corridor intersection point of the plurality of corridor intersection point at an intersection of the spline curve and a radial vector of a plurality of radial vectors, wherein each respective radial vector starts at the centroid line and crosses the spline curve.

6. The system of claim **1**, wherein the memory includes instructions, which, when executed, further cause the processor to:

align, at the processor, the model indicative of the average surgical corridor over patient imaging.

7. The system of claim **6**, wherein the memory includes instructions, which, when executed, further cause the processor to:

generate, at the processor, a 3D model indicative of the average surgical corridor.

8. The system of claim **1**, further comprising:

an image-guided surgical planning system in operative communication with the display device and the processor and/or the memory, the image-guided surgical planning system being configured to:

receive one or more parameters of the average surgical corridor as input; and

display, at the display device, the model indicative of the average surgical corridor over patient imaging, wherein the model is indicative of a volumetric trajectory of a surgical approach.

9. The system of claim **1**, further comprising:

a stereotactic navigation system in operative communication with the display device and the processor and/or the memory, the stereotactic navigation system being configured to:

receive one or more parameters of the average surgical corridor as input; and

display, at the display device, the model indicative of the average surgical corridor over patient imaging, wherein the model is indicative of a volumetric trajectory of a surgical approach.

10. The system of claim **1**, further comprising:

a robotic surgical system in operative communication with the display device and the processor and/or the memory, the robotic surgical system being configured to:

receive the model of the average surgical corridor as input, the model being indicative of a volumetric trajectory of a surgical approach.

11. A method for generating an average surgical corridor from a plurality of datasets, comprising:

obtaining a set of measured data points for a selected dataset of a plurality of selected datasets, the set of measured data points including a first reference point, a second reference point, a target structure reference point, and a plurality of corridor points;

determining, by the processor, an average central axis line and an associated average perpendicular plane for the plurality of selected datasets based on the set of measured data points;

translating, by the processor, the plurality of corridor points associated with a respective selected dataset of the plurality of selected datasets to the average perpendicular plane to generate a plurality of translated corridor points associated with each respective selected dataset of the plurality of selected datasets;

generating, by the processor, a plurality of corridor intersection points that fit a spline curve for each respective selected dataset of the plurality of selected datasets, the spline curve being fit to the plurality of translated corridor points; and

generating a model of an average surgical corridor based on a shape of a surgical corridor of each respective selected dataset of the plurality of selected datasets, the model superimposed over patient imaging for more accurate surgical corridor modeling.

12. The method of claim **11**, further comprising:

translating, by the processor, the set of measured data points for each selected dataset of the plurality of selected datasets from a first 3D coordinate system to a standardized second 3D coordinate system.

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