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Inventor(s)	Joshi; Sanjay M.

Accuracy check and automatic calibration of tracked instruments

Abstract

A system configured to perform an accuracy check of a tracked instrument can include a processing circuitry and memory coupled to the processing circuitry. The memory can include instructions to cause the system to perform operations. The operations can include determining a virtual position of a display device. The operations can further include determining a virtual position of the tracked instrument. The operations can further include determining a point of contact on the display device between the tracked instrument and the display device. The operations can further include determining an expected point of contact on the display device between the tracked instrument and the display device based on the virtual position of the display device and the virtual position of the tracked instrument. The operations can further include determining whether the tracked instrument is accurate based on a difference between the point of contact and the expected point of contact.

Inventors:	**Joshi; Sanjay M. (Andover, MA)**
Applicant:	**GLOBUS MEDICAL, INC.** (Audubon, PA)
Family ID:	**1000008762777**
Assignee:	**Globus Medical, Inc. (Audubon, PA)**
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8574303	12/2012	Sharkey et al.	N/A	N/A
8585420	12/2012	Burbank et al.	N/A	N/A
8594841	12/2012	Zhao et al.	N/A	N/A
8597198	12/2012	Sanborn et al.	N/A	N/A
8600478	12/2012	Verard et al.	N/A	N/A

8603077	12/2012	Cooper et al.	N/A	N/A
8611985	12/2012	Lavallee et al.	N/A	N/A
8613230	12/2012	Blumenkranz et al.	N/A	N/A
8621939	12/2013	Blumenkranz et al.	N/A	N/A
8624537	12/2013	Nowlin et al.	N/A	N/A
8630389	12/2013	Kato	N/A	N/A
8634897	12/2013	Simon et al.	N/A	N/A
8634957	12/2013	Toth et al.	N/A	N/A
8638056	12/2013	Goldberg et al.	N/A	N/A
8638057	12/2013	Goldberg et al.	N/A	N/A
8639000	12/2013	Zhao et al.	N/A	N/A
8641726	12/2013	Bonutti	N/A	N/A
8644907	12/2013	Hartmann et al.	N/A	N/A
8657809	12/2013	Schoepp	N/A	N/A
8660635	12/2013	Simon et al.	N/A	N/A
8666544	12/2013	Moll et al.	N/A	N/A
8675939	12/2013	Moctezuma de la Barrera	N/A	N/A
8678647	12/2013	Gregerson et al.	N/A	N/A
8679125	12/2013	Smith et al.	N/A	N/A
8679183	12/2013	Glerum et al.	N/A	N/A
8682413	12/2013	Lloyd	N/A	N/A
8684253	12/2013	Giordano et al.	N/A	N/A
8685098	12/2013	Glerum et al.	N/A	N/A
8693730	12/2013	Umasuthan et al.	N/A	N/A
8694075	12/2013	Groszmann et al.	N/A	N/A
8696458	12/2013	Foxlin et al.	N/A	N/A
8700123	12/2013	Okamura et al.	N/A	N/A
8706086	12/2013	Glerum	N/A	N/A
8706185	12/2013	Foley et al.	N/A	N/A
8706301	12/2013	Zhao et al.	N/A	N/A
8717430	12/2013	Simon et al.	N/A	N/A
8727618	12/2013	Maschke et al.	N/A	N/A
8734432	12/2013	Tuma et al.	N/A	N/A
8738115	12/2013	Amberg et al.	N/A	N/A
8738181	12/2013	Greer et al.	N/A	N/A
8740882	12/2013	Jun et al.	N/A	N/A
8746252	12/2013	McGrogan et al.	N/A	N/A
8749189	12/2013	Nowlin et al.	N/A	N/A
8749190	12/2013	Nowlin et al.	N/A	N/A
8761930	12/2013	Nixon	N/A	N/A
8764448	12/2013	Yang et al.	N/A	N/A
8771170	12/2013	Mesallum et al.	N/A	N/A
8781186	12/2013	Clements et al.	N/A	N/A
8781630	12/2013	Banks et al.	N/A	N/A
8784385	12/2013	Boyden et al.	N/A	N/A
8786241	12/2013	Nowlin et al.	N/A	N/A
8787520	12/2013	Baba	N/A	N/A
8792704	12/2013	Isaacs	N/A	N/A
8798231	12/2013	Notohara et al.	N/A	N/A
8800838	12/2013	Shelton, IV	N/A	N/A

8808164	12/2013	Hoffman et al.	N/A	N/A
8812077	12/2013	Dempsey	N/A	N/A
8814793	12/2013	Brabrand	N/A	N/A
8816628	12/2013	Nowlin et al.	N/A	N/A
8818105	12/2013	Myronenko et al.	N/A	N/A
8820605	12/2013	Shelton, IV	N/A	N/A
8821511	12/2013	Von Jako et al.	N/A	N/A
8823308	12/2013	Nowlin et al.	N/A	N/A
8827996	12/2013	Scott et al.	N/A	N/A
8828024	12/2013	Farritor et al.	N/A	N/A
8830224	12/2013	Zhao et al.	N/A	N/A
8834489	12/2013	Cooper et al.	N/A	N/A
8834490	12/2013	Bonutti	N/A	N/A
8838270	12/2013	Druke et al.	N/A	N/A
8844789	12/2013	Shelton, IV et al.	N/A	N/A
8855822	12/2013	Bartol et al.	N/A	N/A
8858598	12/2013	Seifert et al.	N/A	N/A
8860753	12/2013	Bhandarkar et al.	N/A	N/A
8864751	12/2013	Prisco et al.	N/A	N/A
8864798	12/2013	Weiman et al.	N/A	N/A
8864833	12/2013	Glerum et al.	N/A	N/A
8867703	12/2013	Shapiro et al.	N/A	N/A
8870880	12/2013	Himmelberger et al.	N/A	N/A
8876866	12/2013	Zappacosta et al.	N/A	N/A
8880223	12/2013	Raj et al.	N/A	N/A
8882803	12/2013	Iott et al.	N/A	N/A
8883210	12/2013	Truncale et al.	N/A	N/A
8888821	12/2013	Rezach et al.	N/A	N/A
8888853	12/2013	Glerum et al.	N/A	N/A
8888854	12/2013	Glerum et al.	N/A	N/A
8894652	12/2013	Seifert et al.	N/A	N/A
8894688	12/2013	Suh	N/A	N/A
8894691	12/2013	Iott et al.	N/A	N/A
8906069	12/2013	Hansell et al.	N/A	N/A
8964934	12/2014	Ein-Gal	N/A	N/A
8992580	12/2014	Bar et al.	N/A	N/A
8996169	12/2014	Lightcap et al.	N/A	N/A
9001963	12/2014	Sowards-Emmerd et al.	N/A	N/A
9002076	12/2014	Khadem et al.	N/A	N/A
9044190	12/2014	Rubner et al.	N/A	N/A
9107683	12/2014	Hourtash et al.	N/A	N/A
9125556	12/2014	Zehavi et al.	N/A	N/A
9131986	12/2014	Greer et al.	N/A	N/A
9215968	12/2014	Schostek et al.	N/A	N/A
9308050	12/2015	Kostrzewski et al.	N/A	N/A
9380984	12/2015	Li et al.	N/A	N/A
9393039	12/2015	Lechner et al.	N/A	N/A
9398886	12/2015	Gregerson et al.	N/A	N/A
9398890	12/2015	Dong et al.	N/A	N/A
9414859	12/2015	Ballard et al.	N/A	N/A

9420975	12/2015	Gutfleisch et al.	N/A	N/A
9492235	12/2015	Hourtash et al.	N/A	N/A
9592096	12/2016	Maillet et al.	N/A	N/A
9750465	12/2016	Engel et al.	N/A	N/A
9757203	12/2016	Hourtash et al.	N/A	N/A
9795354	12/2016	Menegaz et al.	N/A	N/A
9814535	12/2016	Bar et al.	N/A	N/A
9820783	12/2016	Donner et al.	N/A	N/A
9833265	12/2016	Donner et al.	N/A	N/A
9848922	12/2016	Tohmeh et al.	N/A	N/A
9925011	12/2017	Gombert et al.	N/A	N/A
9931025	12/2017	Graetzel et al.	N/A	N/A
10034717	12/2017	Miller et al.	N/A	N/A
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2011/0224825	12/2010	Larkin et al.	N/A	N/A
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2011/0238080	12/2010	Ranjit et al.	N/A	N/A
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2011/0282189	12/2010	Graumann	N/A	N/A
2011/0286573	12/2010	Schretter et al.	N/A	N/A
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2011/0295370	12/2010	Suh et al.	N/A	N/A
2011/0306986	12/2010	Lee	606/130	A61B 34/37
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2012/0051498	12/2011	Koishi	N/A	N/A
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2013/0211420	12/2012	Jensen	N/A	N/A
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2014/0001235	12/2013	Shelton, IV	N/A	N/A
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Primary Examiner: Ip; Jason M

Assistant Examiner: Langhals; Renee C

Background/Summary

FIELD

(1) The present disclosure relates to medical devices and systems, and more particularly, checking accuracy and performing automatic calibration of tracked instruments in a camera tracking systems used for computer assisted navigation during surgery.

BACKGROUND

(2) Surgical operating rooms can contain a diverse range of medical equipment, which can include computer assisted surgical navigation systems, medical imaging devices (e.g., computerized tomography ("CT") scanners, fluoroscopy imaging, etc.), and surgical robots.

(3) A computer assisted surgical navigation system can provide a surgeon with computerized visualization of the present pose of a surgical tool relative to medical images of a patient's anatomy. Camera tracking systems for computer assisted surgical navigation typically use a set of cameras to track pose of a reference array on a surgical tool, which is being positioned by a surgeon during surgery, relative to a patient reference array (also "dynamic reference base" ("DRB")) attached to a patient. The reference arrays allow the camera tracking system to determine a pose of the surgical tool relative to anatomical structure imaged by a medical image of the patient and relative to the patient. The surgeon can thereby use real-time visual feedback of the pose to navigate the surgical tool during a surgical procedure on the patient.

(4) Surgical navigation of instruments using reference elements has become a well-established technique in the operating room. FIG. **10** illustrates an example of a trackable instrument **1010**. The CAD model of an instrument **1010** is associated with a reference element **1020**, so that the CAD model can be overlaid on registered images of patient's anatomy. To ensure fidelity of the overlay, accuracy of the instrument **1010** needs to be verified prior to use. The accuracy check is typically done via bringing the tip **1040** of the tracked instrument into a divot **1050** associated with another reference element. The divot **1050** is typically a cone-shaped depression ending in an apex.

(5) The theoretical position of the tip **1040** is then compared with theoretical position of the divot **1050**. Assuming the user has properly positioned the instrument **1010** in the divot **1050**, the distance between the two positions determines the accuracy of tracked instrument **1010**. If the accuracy check does not pass, that instrument **1010** may not be used.

(6) In some examples, a source of inaccuracy during the accuracy check arises due to it being challenging for a user to place an instrument accurately in the divot. The ideal position for a sharp instrument is along normal from the apex to the base of the cone of the divot. Any deviation of the angle introduces small errors. Furthermore, a bad-acting user may move the position of the instrument to produce a false accuracy number (that appears more accurate).

(7) In additional or alternative examples, a source of inaccuracy during the accuracy check arises due inaccuracy in tracking of the two reference elements (one associated with the tracked instrument and one associated with the divot). The reference element arrays are typically small in size (e.g., on a few centimeters wide) to minimize obstruction of the surgical area. The number of markers is also usually limited to optimize costs and workflow. A larger array with more markers can improve the accuracy of divot position.

(8) In additional or alternative examples, a source of inaccuracy during the accuracy check arises due to a shape of the instrument tip. Blunt tip instruments may not fit well inside the divot and instruments with angled tips or a hook shape can make it even more difficult to properly place the instrument tip in the divot.

(9) In additional or alternative examples, a sources of inaccuracies during the accuracy check includes a deformed instrument. In additional or alternative examples, the source of inaccuracies includes a deformed reference element. Note that a slight angular shift in the reference element can result in very small error for tracking of the reference element, but may result in a much larger error at instrument tip. In additional or alternative examples, the source of inaccuracies include inaccuracies in optical markers due to manufacturing defects, smudges, or inaccurate mounting of optical markers on mounting posts. All these are solvable problems, though. If an instrument can be calibrated at the time of use, the fidelity of tracking can be improved so that the physical tip matches the estimated tip.

SUMMARY

(10) Some embodiments of the present disclosure are directed to performing an accuracy check and calibrating tracked instruments used in surgical procedures.

(11) In some embodiments, a system configured to perform an accuracy check of a tracked instrument is provided. The system includes processing circuitry and memory coupled to the processing circuitry. The memory has instructions stored therein that are executable by the processing circuitry to cause the system to perform operations. The operations include determining a virtual position within a virtual space of a display device. The operations further include determining a virtual position within the virtual space of the tracked instrument. The operations further include determining a point of contact on the display device between the tracked instrument and the display device. The operations further include determining an expected point of contact on the display device between the tracked instrument and the display device based on the virtual position of the display device and the virtual position of the tracked instrument. The operations further include determining whether the tracked instrument is accurate based on a difference between the point of contact and the expected point of contact.

(12) In other embodiments, a system configured to perform an accuracy check of a tracked instrument is provided. The system includes processing circuitry and memory coupled to the processing circuitry. The memory has instructions stored therein that are executable by the processing circuitry to cause the system to perform operations. The operations include determining a first virtual position within a virtual space of an emitter of an imaging device. The operations further include determining a first virtual position within the virtual space of a detector of the imaging device. The operations further include determining a first virtual position within the virtual space of the tracked instrument while the tracked instrument is at a first physical position between the emitter and the detector. The operations further include determining a first expected image of the tracked instrument based on the first virtual position of the emitter, the first virtual position of the detector, and the first virtual position of the tracked instrument. The operations further include obtaining a first image of the tracked instrument while it is positioned at the first physical position between the emitter and the detector. The operations further include determining a second virtual position within the virtual space of the emitter of the imaging device. The operations further include determining a second virtual position within the virtual space of the detector of the imaging device. The operations further include determining a second virtual position within the virtual space of the tracked instrument while the tracked instrument is at a second physical position between the emitter and the detector. The operations further include determining a second expected image of the tracked instrument based on the second virtual position of the emitter, the second virtual position of the detector, and the second virtual position of the tracked instrument. The operations further include obtaining a second image of the tracked instrument while it is positioned between the emitter and the detector, the second image being different than the first image. The

operations further include determining whether the tracked instrument is accurate based on the first expected image, the second expected image, the first image, and the second image.
(13) In other embodiments, a system configured to perform an accuracy check of a tracked instrument is provided. The system includes processing circuitry and memory coupled to the processing circuitry. The memory has instructions stored therein that are executable by the processing circuitry to cause the system to perform operations. The operations include determining a virtual position within a virtual space of the tracked instrument relative to a display device. The operations further include displaying an indication of the virtual position of the tracked instrument on the display device. The operations further include receiving an indication of an actual position of the tracked instrument relative to the display device. The operations further include determining whether the tracked instrument is accurate based on the indication of the actual position relative to the virtual position of the tracked instrument.
(14) Other systems and corresponding methods and computer program products according to embodiments of the inventive subject matter will be or become apparent to one with skill in the art upon review of the following drawings and detailed description. It is intended that all such additional camera tracking system, methods. and computer program products be included within this description, be within the scope of the present inventive subject matter, and be protected by the accompanying claims. Moreover, it is intended that all embodiments disclosed herein can be implemented separately or combined in any way and/or combination.

Description

DESCRIPTION OF THE DRAWINGS
(1) Aspects of the present disclosure are illustrated by way of example and are not limited by the accompanying drawings. In the drawings:
(2) FIG. **1** is an overhead view of personnel wearing extended reality ("XR") headsets during a surgical procedure in a surgical room that includes a camera tracking system for navigated surgery and which may further include a surgical robot for robotic assistance according to some embodiments;
(3) FIG. **2** illustrates the camera tracking system and the surgical robot positioned relative to a patient according to some embodiments;
(4) FIG. **3** further illustrates the camera tracking system and the surgical robot configured according to some embodiments;
(5) FIG. **4** illustrates a block diagram of a surgical system that includes an XR headset, a computer platform, imaging devices, and a surgical robot which are configured to operate according to some embodiments;
(6) FIG. **5** illustrates a patient reference array ("DRB") and a surveillance marker;
(7) FIGS. **6**A-C respectively illustrate a surgical robot with an end-effector, an expanded view of the end-effector, and a surgical tool in accordance with some embodiments;
(8) FIGS. **7**A-B are schematic diagrams illustrating examples of imaging devices according to some embodiments;
(9) FIG. **8** is a block diagram illustrating an example of an imaging system according to some embodiments;
(10) FIG. **9** is a block diagram illustrating an example of an accuracy and calibration module according to some embodiments;
(11) FIG. **10** is a schematic diagram illustrating an example of a tracked instrument according to some embodiments;
(12) FIG. **11** is a schematic diagram illustrating an example of a set of display devices configured to interact with a tracked instrument according to some embodiments;

(13) FIG. **12** is a schematic diagram illustrating an example of the set of display devices of FIG. **11** being contacted by a tracked instrument according to some embodiments;
(14) FIG. **13** is a flow chart illustrating an example of operations for performing an accuracy check on a tracked instrument based on contact with a display device according to some embodiments;
(15) FIG. **14** is a schematic diagram illustrating an example of a C-arm imaging device according to some embodiments;
(16) FIGS. **15**A-B are schematic diagrams illustrating images taken of a tracked instrument using the C-arm imaging device at two different positions according to some embodiments;
(17) FIG. **16** is a flow chart illustrating an example of operations for performing an accuracy check on a tracked instrument based on images taken of the tracked instrument according to some embodiments;
(18) FIG. **17** is a schematic diagram of a display device configured to show an expected position of a tracked instrument according to some embodiments; and
(19) FIGS. **18-20** are flowcharts of operations performed by a system to perform an accuracy check of tracked instruments according to some embodiments.

DETAILED DESCRIPTION

(20) It is to be understood that the present disclosure is not limited in its application to the details of construction and the arrangement of components set forth in the description herein or illustrated in the drawings. The teachings of the present disclosure may be used and practiced in other embodiments and practiced or carried out in various ways. Also, it is to be understood that the phraseology and terminology used herein is for the purpose of description and should not be regarded as limiting. The use of “including,” “comprising,” or “having” and variations thereof herein is meant to encompass the items listed thereafter and equivalents thereof as well as additional items. Unless specified or limited otherwise, the terms “mounted,” “connected,” “supported,” and “coupled” and variations thereof are used broadly and encompass both direct and indirect mountings, connections, supports, and couplings. Further, “connected” and “coupled” are not restricted to physical or mechanical connections or couplings.

(21) The following discussion is presented to enable a person skilled in the art to make and use embodiments of the present disclosure. Various modifications to the illustrated embodiments will be readily apparent to those skilled in the art, and the principles herein can be applied to other embodiments and applications without departing from embodiments of the present disclosure. Thus, the embodiments are not intended to be limited to embodiments shown, but are to be accorded the widest scope consistent with the principles and features disclosed herein. The following detailed description is to be read with reference to the figures, in which like elements in different figures have like reference numerals. The figures, which are not necessarily to scale, depict selected embodiments and are not intended to limit the scope of the embodiments. Skilled artisans will recognize the examples provided herein have many useful alternatives and fall within the scope of the embodiments.

(22) Various embodiments of the present disclosure are directed to providing operations by the camera tracking system to improve registration of candidate markers, such as a surveillance marker, when phantom markers appear in frames of tracking data from tracking cameras. Before describing these embodiments is detail, various components that may be used for performing embodiments in a navigated surgery system are described with reference to FIGS. **1-9**.

(23) FIG. **1** is an overhead view of personnel wearing extended reality (“XR”) headsets **150** during a surgical procedure in a surgical room that includes a camera tracking system **200** for navigated surgery during a surgical procedure and which may further include a surgical robot **100** for robotic assistance, according to some embodiments. FIG. **2** illustrates the camera tracking system **200** and the surgical robot **100** positioned relative to a patient, according to some embodiments. FIG. **3** further illustrates the camera tracking system **200** and the surgical robot **100** configured according to some embodiments. FIG. **4** illustrates a block diagram of a surgical system that includes an XR

headset **150**, a computer platform **400**, imaging devices **420**, and the surgical robot **100** which are configured to operate according to some embodiments. FIG. **5** illustrates a patient reference array **116** (also "dynamic reference base" (DRB)) and a surveillance marker **500**.

(24) The XR headset **150** may be configured to augment a real-world scene with computer generated XR images. The XR headset **150** may be configured to provide an augmented reality ("AR") viewing environment by displaying the computer generated XR images on a see-through display screen that allows light from the real-world scene to pass therethrough for combined viewing by the user. Alternatively, the XR headset **150** may be configured to provide a virtual reality ("VR") viewing environment by preventing or substantially preventing light from the real-world scene from being directly viewed by the user while the user is viewing the computer-generated AR images on a display screen. The XR headset **150** can be configured to provide both AR and VR viewing environments. Thus, the term XR headset can referred to as an AR headset or a VR headset.

(25) Referring to FIGS. **1-5**, the surgical robot **100** may include, for example, one or more robot arms **104**, a display **110**, an end-effector **112**, for example, including a guide tube **114**, and an end effector reference array which can include one or more tracking markers. A patient reference array **116** ("DRB") has a plurality of tracking markers **117** and is secured directly to the patient **210** (e.g., to a bone of the patient **210**). A spaced apart surveillance marker **500** (FIG. **5**) has a single marker **502** connected to a shaft that is secured directly to the patient **210** at a spaced apart location from the patient reference array **116**. Another reference array **170** is attached or formed on an instrument, surgical tool, surgical implant device, etc.

(26) The camera tracking system **200** includes tracking cameras **204** which may be spaced apart stereo cameras configured with partially overlapping field-of-views. The camera tracking system **200** can have any suitable configuration of arm(s) **202** to move, orient, and support the tracking cameras **204** in a desired location, and may contain at least one processor operable to track location of an individual marker and pose of an array of markers. As used herein, the term "pose" refers to the location (e.g., along 3 orthogonal axes) and/or the rotation angle (e.g., about the 3 orthogonal axes) of markers (e.g., DRB) relative to another marker (e.g., surveillance marker) and/or to a defined coordinate system (e.g., camera coordinate system). A pose may therefore be defined based on only the multidimensional location of the markers relative to another marker and/or relative to the defined coordinate system, based on only the multidimensional rotational angles of the markers relative to the other marker and/or to the defined coordinate system, or based on a combination of the multidimensional location and the multidimensional rotational angles. The term "pose" therefore is used to refer to location, rotational angle, or combination thereof.

(27) The tracking cameras **204** may include, e.g., infrared cameras (e.g., bifocal or stereophotogrammetric cameras), operable to identify, for example, active and passive tracking markers for single markers (e.g., surveillance marker **500**) and reference arrays which can be formed on or attached to the patient **210** (e.g., patient reference array, DRB), end effector **112** (e.g., end effector reference array), XR headset(s) **150** worn by a surgeon **120** and/or a surgical assistant **126**, etc. in a given measurement volume of a camera coordinate system while viewable from the perspective of the tracking cameras **204**. The tracking cameras **204** may scan the given measurement volume and detect light that is emitted or reflected from the markers in order to identify and determine locations of individual markers and poses of the reference arrays in three-dimensions. For example, active reference arrays may include infrared-emitting markers that are activated by an electrical signal (e.g., infrared light emitting diodes ("LEDs")), and passive reference arrays may include retro-reflective markers that reflect infrared light (e.g., they reflect incoming IR radiation into the direction of the incoming light), for example, emitted by illuminators on the tracking cameras **204** or other suitable device.

(28) The XR headsets **150** may each include tracking cameras (e.g., spaced apart stereo cameras) that can track location of a surveillance marker and poses of reference arrays within the XR camera

headset field-of-views ("FOVs") **152** and **154**, respectively. Accordingly, as illustrated in FIG. **1**, the location of the surveillance marker and the poses of reference arrays on various objects can be tracked while in the FOVs **152** and **154** of the XR headsets **150** and/or a FOV **600** of the tracking cameras **204**.

(29) FIGS. **1-2** illustrate a potential configuration for the placement of the camera tracking system **200** and the surgical robot **100** in an operating room environment. Computer-aided navigated surgery can be provided by the camera tracking system controlling the XR headsets **150** and/or other displays **34**, **36**, and **110** to display surgical procedure navigation information. The surgical robot **100** is optional during computer-aided navigated surgery.

(30) The camera tracking system **200** may operate using tracking information and other information provided by multiple XR headsets **150** such as inertial tracking information and optical tracking information (frames of tracking data). The XR headsets **150** operate to display visual information and may play-out audio information to the wearer. This information can be from local sources (e.g., the surgical robot **100** and/or other medical), remote sources (e.g., patient medical image server), and/or other electronic equipment. The camera tracking system **200** may track markers in 6 degrees-of-freedom ("6DOF") relative to three axes of a 3D coordinate system and rotational angles about each axis. The XR headsets **150** may also operate to track hand poses and gestures to enable gesture-based interactions with "virtual" buttons and interfaces displayed through the XR headsets **150** and can also interpret hand or finger pointing or gesturing as various defined commands. Additionally, the XR headsets **150** may have a 1-10× magnification digital color camera sensor called a digital loupe. In some embodiments, one or more of the XR headsets **150** are minimalistic XR headsets that display local or remote information but include fewer sensors and are therefore more lightweight.

(31) An "outside-in" machine vision navigation bar supports the tracking cameras **204** and may include a color camera. The machine vision navigation bar generally has a more stable view of the environment because it does not move as often or as quickly as the XR headsets **150** while positioned on wearers' heads. The patient reference array **116** (DRB) is generally rigidly attached to the patient with stable pitch and roll relative to gravity. This local rigid patient reference **116** can serve as a common reference for reference frames relative to other tracked arrays, such as a reference array on the end effector **112**, instrument reference array **170**, and reference arrays on the XR headsets **150**.

(32) During a surgical procedure using surgical navigation, the surveillance marker **500** is affixed to the patient to provide information on whether the patient reference array **116** has shifted. For example, during a spinal fusion procedure with planned placement of pedicle screw fixation, two small incisions are made over the posterior superior iliac spine bilaterally. The DRB and the surveillance marker are then affixed to the posterior superior iliac spine bilaterally. If the surveillance marker's **500** location changes relative to the patient reference array **116**, the camera tracking system **200** may display a meter indicating the amount of movement and/or may display a pop-up warning message to inform the user that the patient reference array may have been bumped. If the patient reference array has indeed been bumped, the registration of the patient reference array to the tracked coordinate system may be invalid and could result in erroneous navigation which is off target.

(33) When present, the surgical robot (also "robot") may be positioned near or next to patient **210**. The robot **100** can be positioned at any suitable location near the patient **210** depending on the area of the patient **210** undergoing the surgical procedure. The camera tracking system **200** may be separated from the robot system **100** and positioned at the foot of patient **210**. This location allows the tracking camera **200** to have a direct visual line of sight to the surgical area **208**. In the configuration shown, the surgeon **120** may be positioned across from the robot **100**, but is still able to manipulate the end-effector **112** and the display **110**. A surgical assistant **126** may be positioned across from the surgeon **120** again with access to both the end-effector **112** and the display **110**. If

desired, the locations of the surgeon **120** and the assistant **126** may be reversed. An anesthesiologist **122**, nurse or scrub tech can operate equipment which may be connected to display information from the camera tracking system **200** on a display **34**.

(34) With respect to the other components of the robot **100**, the display **110** can be attached to the surgical robot **100** or in a remote location. End-effector **112** may be coupled to the robot arm **104** and controlled by at least one motor. In some embodiments, end-effector **112** can comprise a guide tube **114**, which is configured to receive and orient a surgical instrument, tool, or implant used to perform a surgical procedure on the patient **210**.

(35) As used herein, the term "end-effector" is used interchangeably with the terms "end-effectuator" and "effectuator element." The term "instrument" is used in a non-limiting manner and can be used interchangeably with "tool" and "implant" to generally refer to any type of device that can be used during a surgical procedure in accordance with embodiments disclosed herein. Example instruments, tools, and implants include, without limitation, drills, screwdrivers, saws, dilators, retractors, probes, implant inserters, and implant devices such as a screws, spacers, interbody fusion devices, plates, rods, etc. Although generally shown with a guide tube **114**, it will be appreciated that the end-effector **112** may be replaced with any suitable instrumentation suitable for use in surgery. In some embodiments, end-effector **112** can comprise any known structure for effecting the movement of the surgical instrument in a desired manner.

(36) The surgical robot **100** is operable to control the translation and orientation of the end-effector **112**. The robot **100** may move the end-effector **112** under computer control along x-, y-, and z-axes, for example. The end-effector **112** can be configured for selective rotation about one or more of the x-, y-, and z-axis, and a Z Frame axis, such that one or more of the Euler Angles (e.g., roll, pitch, and/or yaw) associated with end-effector **112** can be selectively computer controlled. In some embodiments, selective control of the translation and orientation of end-effector **112** can permit performance of medical procedures with significantly improved accuracy compared to conventional robots that utilize, for example, a 6DOF robot arm comprising only rotational axes. For example, the surgical robot **100** may be used to operate on patient **210**, and robot arm **104** can be positioned above the body of patient **210**, with end-effector **112** selectively angled relative to the z-axis toward the body of patient **210**.

(37) In some example embodiments, the XR headsets **150** can be controlled to dynamically display an updated graphical indication of the pose of the surgical instrument so that the user can be aware of the pose of the surgical instrument at all times during the procedure.

(38) In some further embodiments, surgical robot **100** can be operable to correct the path of a surgical instrument guided by the robot arm **104** if the surgical instrument strays from the selected, preplanned trajectory. The surgical robot **100** can be operable to permit stoppage, modification, and/or manual control of the movement of end-effector **112** and/or the surgical instrument. Thus, in use, a surgeon or other user can use the surgical robot **100** as part of computer assisted navigated surgery, and has the option to stop, modify, or manually control the autonomous or semi-autonomous movement of the end-effector **112** and/or the surgical instrument.

(39) Reference arrays of markers can be formed on or connected to robot arms **102** and/or **104**, the end-effector **112** (e.g., end-effector array **114** in FIG. **2**), and/or a surgical instrument (e.g., instrument array **170**) to track poses in 6DOF along 3 orthogonal axes and rotation about the axes. The reference arrays enable each of the marked objects (e.g., the end-effector **112**, the patient **210**, and the surgical instruments) to be tracked by the tracking camera **200**, and the tracked poses can be used to provide navigated guidance during a surgical procedure and/or used to control movement of the surgical robot **100** for guiding the end-effector **112** and/or an instrument manipulated by the end-effector **112**.

(40) Referring to FIG. **3** the surgical robot **100** may include a display **110**, upper arm **102**, lower arm **104**, end-effector **112**, vertical column **312**, casters **314**, a table **318**, and ring **324** which uses lights to indicate statuses and other information. Cabinet **106** may house electrical components of

surgical robot **100** including, but not limited, to a battery, a power distribution module, a platform interface board module, and a computer. The camera tracking system **200** may include a display **36**, tracking cameras **204**, arm(s) **202**, a computer housed in cabinet **330**, and other components.

(41) In computer-assisted navigated surgeries, perpendicular 2D scan slices, such as axial, sagittal, and/or coronal views, of patient anatomical structure are displayed to enable user visualization of the patient's anatomy alongside the relative poses of surgical instruments. An XR headset or other display can be controlled to display one or more 2D scan slices of patient anatomy along with a 3D graphical model of anatomy. The 3D graphical model may be generated from a 3D scan of the patient, e.g., by a CT scan device, and/or may be generated based on a baseline model of anatomy which isn't necessarily formed from a scan of the patient.

Example Surgical System

(42) FIG. **4** illustrates a block diagram of a surgical system that includes an XR headset **150**, a computer platform **400**, imaging devices **420**, and a surgical robot **100** which are configured to operate according to some embodiments.

(43) The imaging devices **420** may include a C-arm imaging device, an O-arm imaging device, and/or a patient image database. The XR headset **150** provides an improved human interface for performing navigated surgical procedures. The XR headset **150** can be configured to provide functionalities, e.g., via the computer platform **400**, that include without limitation any one or more of: identification of hand gesture based commands, display XR graphical objects on a display device **438** of the XR headset **150** and/or another display device. The display device **438** may include a video projector, flat panel display, etc. The user may view the XR graphical objects as an overlay anchored to particular real-world objects viewed through a see-through display screen. The XR headset **150** may additionally or alternatively be configured to display on the display device **438** video streams from cameras mounted to one or more XR headsets **150** and other cameras.

(44) Electrical components of the XR headset **150** can include a plurality of cameras **430**, a microphone **432**, a gesture sensor **434**, a pose sensor (e.g., inertial measurement unit ("IMU")) **436**, the display device **438**, and a wireless/wired communication interface **440**. The cameras **430** of the XR headset **150** may be visible light capturing cameras, near infrared capturing cameras, or a combination of both.

(45) The cameras **430** may be configured to operate as the gesture sensor **434** by tracking for identification user hand gestures performed within the field of view of the camera(s) **430**. Alternatively, the gesture sensor **434** may be a proximity sensor and/or a touch sensor that senses hand gestures performed proximately to the gesture sensor **434** and/or senses physical contact, e.g., tapping on the sensor **434** or its enclosure. The pose sensor **436**, e.g., IMU, may include a multi-axis accelerometer, a tilt sensor, and/or another sensor that can sense rotation and/or acceleration of the XR headset **150** along one or more defined coordinate axes. Some or all of these electrical components may be contained in a head-worn component enclosure or may be contained in another enclosure configured to be worn elsewhere, such as on the hip or shoulder.

(46) As explained above, a surgical system includes the camera tracking system **200** which may be connected to a computer platform **400** for operational processing and which may provide other operational functionality including a navigation controller **404** and/or of an XR headset controller **410**. The surgical system may include the surgical robot **100**. The navigation controller **404** can be configured to provide visual navigation guidance to an operator for moving and positioning a surgical tool relative to patient anatomical structure based on a surgical plan, e.g., from a surgical planning function, defining where a surgical procedure is to be performed using the surgical tool on the anatomical structure and based on a pose of the anatomical structure determined by the camera tracking system **200**. The navigation controller **404** may be further configured to generate navigation information based on a target pose for a surgical tool, a pose of the anatomical structure, and a pose of the surgical tool and/or an end effector of the surgical robot **100**, where the steering information is displayed through the display device **438** of the XR headset **150** and/or another

display device to indicate where the surgical tool and/or the end effector of the surgical robot **100** should be moved to perform the surgical plan.

(47) The electrical components of the XR headset **150** can be operatively connected to the electrical components of the computer platform **400** through the wired/wireless interface **440**. The electrical components of the XR headset **150** may be operatively connected, e.g., through the computer platform **400** or directly connected, to various imaging devices **420**, e.g., the C-arm imaging device, the I/O-arm imaging device, the patient image database, and/or to other medical equipment through the wired/wireless interface **440**.

(48) The surgical system may include a XR headset controller **410** that may at least partially reside in the XR headset **150**, the computer platform **400**, and/or in another system component connected via wired cables and/or wireless communication links. Various functionality is provided by software executed by the XR headset controller **410**. The XR headset controller **410** is configured to receive information from the camera tracking system **200** and the navigation controller **404**, and to generate an XR image based on the information for display on the display device **438**.

(49) The XR headset controller **410** can be configured to operationally process frames of tracking data from tracking cameras from the cameras **430** (tracking cameras), signals from the microphone **1620**, and/or information from the pose sensor **436** and the gesture sensor **434**, to generate information for display as XR images on the display device **438** and/or as other for display on other display devices for user viewing. Thus, the XR headset controller **410** illustrated as a circuit block within the XR headset **150** is to be understood as being operationally connected to other illustrated components of the XR headset **150** but not necessarily residing within a common housing or being otherwise transportable by the user. For example, the XR headset controller **410** may reside within the computer platform **400** which, in turn, may reside within the cabinet **330** of the camera tracking system **200**, the cabinet **106** of the surgical robot **100**, etc.

(50) Turning now to FIGS. **6**A-**6**C, the surgical robot system **100** relies on accurate positioning of the end-effector **112**, surgical instruments **608**, and/or the patient **210** (e.g., patient reference array **116**) relative to the desired surgical area. In the embodiments shown in FIGS. FIGS. **6**A-**6**C, the reference arrays include tracking markers **118**, **804** which are rigidly attached to a portion of the instrument **608** and/or end-effector **112**.

(51) FIG. **6**A depicts part of the surgical robot system **100** with the robot **102** including base **106**, robot arm **104**, and end-effector **112**. The other elements, not illustrated, such as the display, marker tracking cameras, etc. may also be present as described herein. FIG. **6**B depicts a close-up view of the end-effector **112** with guide tube **114** and a reference array that includes a plurality of tracking markers **118** rigidly affixed to the end-effector **112**. In this embodiment, the plurality of tracking markers **118** are attached to the end-effector **112** configured as a guide tube. FIG. **6**C depicts an instrument **608** (in this case, a probe) with a plurality of tracking markers **804** rigidly affixed to the instrument **608**. As described elsewhere herein, the instrument **608** could include any suitable surgical instrument, such as, but not limited to, guide wire, cannula, a retractor, a drill, a reamer, a screwdriver, an insertion instrument, a removal instrument, or the like.

(52) In FIG. **6**C, the reference array **612** functions as the handle **620** of the instrument **608**. Four markers **804** are attached to the handle **620** in a manner that is out of the way of the shaft **622** and tip **624**. Stereophotogrammetric tracking by the tracking camera **200** of these four markers **804** allows the instrument **608** to be tracked as a rigid body and for the system **100** to precisely determine the location of the tip **624** and the orientation of the shaft **622** while the instrument **608** is moved within view of tracking camera **200**.

(53) To enable automatic tracking of one or more instruments **608**, end-effector **112**, or other object to be tracked in 3D (e.g., multiple rigid bodies), the markers **118**, **804** on each instrument **608**, end-effector **112**, or the like, may be arranged asymmetrically with a known inter-marker spacing. The reason for asymmetric alignment is so that it is unambiguous which marker **118**, **804** corresponds to a particular pose on the rigid body and whether markers **118**, **804** are being viewed from the

front or back, i.e., mirrored. For example, if the markers **118**, **804** were arranged in a square on the instrument **608** or end-effector **112**, it would be unclear to the system **100**, **300**, **600** which marker **118**, **804** corresponded to which corner of the square. For example, for the instrument **608**, it would be unclear which marker **804** was closest to the shaft **622**. Thus, it would be unknown which way the shaft **622** was extending from the array **612**. Accordingly, each array **612** and thus each instrument **608**, end-effector **112**, or other object to be tracked should have a unique marker pattern to allow it to be distinguished from other instruments **608** or other objects being tracked.

(54) Asymmetry and unique marker patterns allow the tracking camera **200** and system **100** to detect individual markers **118**, **804** then to check the marker spacing against a stored template to determine which instrument **608**, end-effector **112**, or another object they represent. Detected markers **118**, **804** can then be sorted automatically and assigned to each tracked object in the correct order. Without this information, rigid body calculations could not then be performed to extract key geometric information, for example, such as instrument tip **624** and alignment of the shaft **622**, unless the user manually specified which detected marker **118**, **804** corresponded to which position on each rigid body.

(55) FIGS. **7**A-B illustrate medical imaging systems **1304** that may be used in conjunction with robot system **100** and/or navigation systems to acquire pre-operative, intra-operative, post-operative, and/or real-time image data of patient **210**. Any appropriate subject matter may be imaged for any appropriate procedure using the imaging system **1304**. The imaging system **1304** may be any imaging device such as a C-arm **1308** device, an O-arm **1306** device, a fluoroscopy imaging device, a magnetic resonance imaging scanner, etc. It may be desirable to take x-rays of patient **210** from a number of different positions, without the need for frequent manual repositioning of patient **210** which may be required in an x-ray system. As illustrated in FIG. **7**A, the imaging system **1304** may be in the form of a C-arm **1308** that includes an elongated C-shaped member terminating in opposing distal ends **1312** of the "C" shape. C-shaped member **1130** may further comprise an x-ray source **1314** and an image receptor **1316**. The space within C-arm **1308** of the arm may provide room for the physician to attend to the patient substantially free of interference from x-ray support structure **1318**. As illustrated in FIG. **7**B, the imaging system **1304** may include an O-arm imaging device **1306** having a gantry housing **1324** attached to a support structure imaging device support structure **1328**, such as a wheeled mobile cart **1330** with wheels **1332**, which may enclose an image capturing portion, not illustrated. The image capturing portion may include an x-ray source and/or emission portion and an x-ray receiving and/or image receiving portion, which may be disposed about one hundred and eighty degrees from each other and mounted on a rotor (not illustrated) relative to a track of the image capturing portion. The image capturing portion may be operable to rotate three hundred and sixty degrees during image acquisition. The image capturing portion may rotate around a central point and/or axis, allowing image data of patient **210** to be acquired from multiple directions or in multiple planes. Although certain imaging systems **1304** are exemplified herein, it will be appreciated that any suitable imaging system may be selected by one of ordinary skill in the art.

(56) FIG. **8** illustrates a block diagram of components of a medical imaging system configured in accordance with some embodiments of the present disclosure. The medical imaging system includes a controller **3200**, a imaging arm **3240** (e.g., a C-arm or an O-arm), a linear actuator and/or rotary actuator **3250** connected to an X-ray beam emitter or collector **3260**. The controller **3200** includes an image processor **3210**, a general processor **3220**, and an I/O interface **3230**. The image processor **3210** performs image processing to combine sets of images to generate a three-dimensional image of the scanned volume. The general processor **3220** is used to perform various embodiments of the present disclosure. The I/O interface **3230** communicatively couples the controller **3200** to other components of the medical imaging system. The imaging arm **3240** includes motors **3245** used to move the collector and emitter along an arc, e.g., three hundred and sixty degrees, during image acquisition. Motors **3245** are controlled by C-arm the controller **3200**.

The controller **3200** can also control movement of the linear actuator and/or rotary actuator **3250**.
(57) FIG. **9** illustrates an example of an accuracy and calibration module **3300**. The accuracy and calibration module **3330** can include an interface **3310**, a processing circuitry **3320**, and a memory **3330**. In some examples, the accuracy and calibration module is part of a system (e.g., an imaging system or a camera tracking system). The memory **3330** can include instructions stored therein that are executable by the processing circuitry to perform operations according to some embodiments herein.
(58) Embodiments that include performing an accuracy check and/or calibrating of a tracked instrument based on contact with a touch sensor (e.g., a touchscreen of a display device) are described below.
(59) In some embodiments, multiple points of contact (e.g., touch positions from the tip of a tracked instrument) can be detected by one or more touchpads that are themselves tracked by navigation camera. The instruments and the pressure touchpads can each have associated reference elements that are tracked by the navigation camera. In some examples, the touchpads are sensitive to pressure, capacitance, or resistance.
(60) FIG. **11** illustrates an example of a set of touchpads **1110** coupled together to create an opening for accepting a tip of the tracked instrument. The associated reference element **1120** is coupled to the touchpads. In this example, the touchpads and reference arrays are securely housed in a supporting structure **1130** to reduce movement.
(61) The touchpads **1110** can capture location of pressure points. Resistive touchpads are especially useful, since they do not rely on capacitance of the object. When an instrument is brought in the wedge, it touches at least two points on the touchpads **1110**. The touchpads **1110** then send the location of sensed points to the system. The system also receives the position of pose of the touchpads and instruments via their associated reference elements **1120**. Thus, the system can calculate the theoretical position of the tip of the instrument under test. It can then compare the tip location to the location reported by the three touchpads **1110**.
(62) Typically, the bottom touchpad would report position of a sharp or semi-sharp instrument tip. For a broader instrument, such as an Osteotome, there will be multiple touch-points on the bottom touchpads while the side touchpads will report straight lines of touch-points. The approximate position of the CAD model with respect to the touchpads is known already to the system based on the tracking information reported by the camera. Thus, the accuracy of the physical model can be calculated.
(63) FIG. **12** illustrates an example of a tip of a tracked instrument **1240** contacting the touchpads **1110**. The wedge shape of the opening between the touchpads **1110** allows an accuracy check of instruments with tips that are too big to fit in a typical divot used in navigation arrays.
(64) FIG. **13** illustrates an example of operations to perform an accuracy check and calibrate a tracked instrument based on contact between the tracked instrument and the display devices. To calibrate an instrument, the reported touchpad points are compared against the theoretical model. First, the user touches instrument tip on all three touchpads in a way that reference elements of both the instrument and the touchpad structure are visible to the tracking camera. The theoretical position of the instrument tip with respect to touchpads is then calculated. This serves as the initial position estimate of the instrument tip. Since the relative position of three touchpads is known, the theoretical touchpoints of the CAD model for each touchpad are then calculated. The optimization tweaks the position and pose of the CAD model of the instrument to obtain a close match between the theoretical touchpoints and the actual ones as shown in the algorithm below.
(65) In some embodiments, these operations improve accuracy checks for instruments without a sharp tip or instruments that are too wide to fit in a traditional divot. In additional or alternative embodiments, these operation allow re-calibration or correction of theoretical instrument tip location based on actual measurements.
(66) FIG. **18** illustrates an example of operations performed by a system to perform an accuracy

check and/or calibration of a tracked instrument based on a point of contact between the tracked instrument and a touch sensor. Although the operations are described below as being performed by the accuracy and calibration module **3300**, any suitable system (e.g., an imaging system or a tracking system) can perform these operations.

(67) At block **1810**, processing circuitry **3320** determines a virtual position of the touch sensor. In some examples, the term virtual position is used herein to describe a virtual location and a virtual pose of an object. In some embodiments, the system includes a camera. Determining the virtual position of the touch sensor includes: determining information about a shape of the touch sensor relative to a reference element coupled to the touch sensor; capturing, via the camera, an image of the reference element coupled to the touch sensor; determining a virtual position of the reference element coupled to the touch sensor relative to a dynamic reference base ("DRB") based on the image of the reference element coupled to the touch sensor; and determining the virtual position of the touch sensor based on the information about the shape of the touch sensor and the virtual position of the reference element coupled to the touch sensor.

(68) At block **1820**, processing circuitry **3320** determines a virtual position of the tracked instrument. In some embodiments, the virtual position of the touch sensor and the virtual position of the tracked instrument are within the same virtual space (e.g., relative to a common reference point).

(69) In additional or alternative embodiments, the system includes a camera. determining the virtual position of the tracked instrument includes: determining information about a shape of the tracked instrument relative to a reference element coupled to the tracked instrument; capturing, via the camera, an image of the reference element coupled to the tracked instrument; determining a virtual position of the reference element coupled to the tracked instrument relative to the DRB based on the image of the reference element coupled to the tracked instrument; and determining the virtual position of the tracked instrument based on the shape of the tracked instrument and the reference element coupled to the tracked instrument.

(70) At block **1830**, processing circuitry **3320** determines a point of contact on a touch sensor between the tacked instrument and the touch sensor. In some embodiments, the system includes the touch sensor and the touch sensor includes a touchscreen (e.g., a pressure sensitive, resistance sensitive, or capacitance sensitive touchscreen). In some examples the touch sensor is part of a display device. Determining the point of contact includes detecting a location on the touchscreen that the tracked instrument is touching.

(71) In additional or alternative embodiments, the touch sensor includes a plurality of touch sensors coupled together to form an opening. Determining the point of contact on the touch sensor includes determining a plurality of points of contact, each point of contact between one of the touch sensors of the plurality of touch sensors and the tracked instrument while the tracked instrument is positioned in the opening.

(72) At block **1840**, processing circuitry **3320** determines an expected point of contact on the touch sensor based on the virtual position of the touch sensor and the virtual position of the tracked instrument.

(73) In some embodiments, information about the shape of the tracked instrument is determined and the information an intended position of a tip of the tracked instrument relative to a reference element coupled to the tracked instrument. Determining the point of contact on the touch sensor can include determining a point of contact between the tip of the tracked instrument and the touch sensor. Determining the expected point of contact on the touch sensor can include determining a point of contact between the tip of the tracked instrument and the touch sensor based on the virtual position of the touch sensor and the virtual position of the tracked instrument.

(74) At block **1850**, processing circuitry **3320** displays an indication of the expected point of contact. In some embodiments, the system includes a display device that includes the touch sensor. Determining the point of contact on the touch sensor between the tracked instrument and the touch

sensor includes receiving an indication of the point of contact on the touch sensor from a user in response to displaying the indication of the expected point of contact.
(75) At block **1860**, processing circuitry **3320** determines whether the tracked instrument is accurate based on a difference between the point of contact and the expected point of contact.
(76) In some embodiments, determining the point of contact on the touch sensor includes determining a plurality of points of contact between the tracked instrument and the touch sensor. Determining the expected point of contact on the touch sensor includes determining a plurality of expected points of contact between the tracked instrument and the touch sensor based on the virtual position of the touch sensor and the virtual position of the tracked instrument. Determining whether the tracked instrument is accurate includes determining whether the tracked instrument is accurate based on a difference between the plurality of points of contact and the plurality of expected points of contact.
(77) At block **1870**, processing circuitry **3320** performs an action based on whether the tracked instrument is accurate.
(78) In some embodiments, determining whether the tracked instrument is accurate includes determining that the difference exceeds a predetermined threshold. In some examples, performing the action includes outputting an indication that the tracked instrument is not suitable for use. In additional or alternative examples, performing the action includes calibrating a tracking system used to track the tracked instrument using at least one of the point of contact, the expected point of contact, and the difference.
(79) Various operations of FIG. **18** may be optional. For example, blocks **1850** and **1870** may be optional in some embodiments.
(80) Embodiments that include performing an accuracy check and/or calibrating a tracked instrument based on an image taken by a tracked imaging device are described below.
(81) In some embodiments, multiple x-ray views of one or more tracked instruments are taken with a Fluoroscope that is tracked by a navigation camera using an attached registration fixture. Such registration fixtures are commonly used for surgical navigation using fluoroscopy.
(82) FIG. **14** illustrates an example of an imaging device **1410** including an x-ray emitter **1420** and a x-ray detector **1430**. The registration fixture **1440** is coupled to a predetermine portion of the imaging device **1410**.
(83) The registration fixture **1440** typically includes fiducials in two planes at known positions. These fiducials are then detected in images captured by a navigation camera. Using the known positions, the relative position of the emitter **1420** is then computed. The position of the detector **1440** is tracked using the attached reference element **1440** via a navigation camera. When an instrument tracked with a reference element is brought between the emitter and detector, its relative position with respect to registration fixture **1440** is calculated.
(84) The CAD model of the associated instrument tip can then be projected on the fluoroscopy image to achieve navigation. Since the registration fixture can move after the x-ray image is captured, often a different reference element, called a DRB is solidly attached to the patient, so that all tracked positions are relative to the fixed DRB.
(85) Since the rendered position of an instrument is only in 2D, at least two views, roughly orthogonal to each other, are used to track the instrument on two roughly orthogonal views to obtain pseudo-3D navigation.
(86) FIGS. **15**A-B illustrate an example in which a wedge-shaped tracked instrument is placed between the emitter **1420** and detector **1430**, such that its views are captured by the fluoroscope in two positions. The corresponding images **1570***a-b* below the fluoroscope show the instrument profile in different angles. Note that most instruments are solid and are made up of metal, which absorbs most x-rays and shows up dark on an x-ray image.
(87) Since the theoretical position of the tip of the instrument **1550** is known via the attached reference element **1560**, the accuracy of the projection can be compared to the theoretical

projection by detecting the dark instrument shape in a bright image. Thus, the accuracy can be calculated without needing a divot.

(88) If multiple instruments can be placed within the field of view of the x-ray image, accuracy of all of them can be calculated simultaneously.

(89) FIG. **16** illustrates an example of operations for performing an accuracy check and/or calibrating a tracked instrument using images of the tracked instrument. The x-ray views of an instrument are obtained as described above. The theoretical position of the instrument tip projected in the views then calculated. This serves as the initial position estimate of the instrument tip. Using the projection matrix, the theoretical view of the CAD model in each x-ray is then calculated. The optimization tweaks the position and pose of the CAD model of the instrument to obtain a close match between the CAD view and actual image as shown in the algorithm below.

(90) In some examples, this is the same problem as matching a CT scan to multiple Fluoroscopy images in CTFluoro registration, except in this case a CAD model is used instead of a CT scan to compute dynamically rendered radiograph ("DRR").

(91) In some embodiments, these operations do not rely on a sharp tipped instrument fitting snugly in a divot, and can be used for accuracy checks of all types of instrument tips.

(92) In additional or alternative embodiments, these operations improve accuracy checks for instruments without a sharp or straight tip.

(93) In additional or alternative embodiments, these operations allow re-calibration or correction of theoretical instrument tip location based on actual measurements.

(94) In additional or alternative embodiments, these operations enable accuracy checks and re-calibration of multiple instruments simultaneously.

(95) FIG. **19** illustrates an example of operations performed by a system to perform an accuracy check and/or calibration of a tracked instrument based on a pair of images taken by an imaging device. Although the operations are described below as being performed by the accuracy and calibration module **3300**, any suitable system (e.g., an imaging system or a tracking system) can perform these operations.

(96) At block **1910**, processing circuitry **3320** determines a first virtual position of an emitter. In some embodiments, the system includes a tracking camera and an imaging device including the emitter and a detector. Determining the first virtual position of the emitter includes: capturing, via the camera, an image of a reference element coupled to the imaging device; determining a virtual position of the reference element coupled to the imaging device (e.g., relative to a dynamic reference base ("DRB")) based on the image of the reference element coupled to the imaging device; and determining the virtual position of the emitter based on predetermined information indicating a position of the emitter relative to the reference element coupled to the imaging device and the virtual position of the reference element coupled to the imaging device. In additional or alternative embodiments, the virtual position of the emitter is determined based on predetermined information indicating a position of the emitter relative to the detector and a virtual position of the detector.

(97) At block **1915**, processing circuitry **3320** determines a first virtual position of a detector. In some embodiments, the system includes a tracking camera and an imaging device including the emitter and the detector. Determining the first virtual position of the detector includes: capturing, via the camera, an image of a reference element coupled to the imaging device; determining a virtual position of the reference element coupled to the imaging device (e.g., relative to a DRB) based on the image of the reference element coupled to the imaging device; and determining the virtual position of the detector based on predetermined information indicating a position of the detector relative to the reference element coupled to the imaging device and the virtual position of the reference element coupled to the imaging device.

(98) At block **1920**, processing circuitry **3320** determines a first virtual position of a tracked instrument while the tracked instrument is at a first physical position between the emitter and the

detector. In some embodiments, the system includes a tracking camera. Determining the first virtual position of the tracked instrument includes: determining information about a shape of the tracked instrument relative to a reference element coupled to the tracked instrument; capturing, via the camera, an image of the reference element coupled to the tracked instrument; determining a virtual position of the reference element coupled to the tracked instrument (e.g., relative to the DRB) based on the image of the reference element coupled to the tracked instrument; and determining the first virtual position of the tracked instrument based on the shape of the tracked instrument and the reference element coupled to the tracked instrument.

(99) In additional or alternative embodiments, determining the information about the shape of the tracked instrument includes determining an intended position of a tip of the tracked instrument relative to the reference element coupled to the tracked instrument.

(100) At block **1925**, processing circuitry **3320** determines a first expected image of the tracked instrument. In some embodiments, the first expected image of the tracked instrument is determined by simulating operation of the emitter and the detector based on the first virtual position of the emitter, the first virtual position of the detector, the first virtual position of the tracked instrument, and a predetermined shape of the tracked instrument.

(101) At block **1930**, processing circuitry **3320** obtains a first image of the tracked instrument. In some embodiments, obtaining the first image of the tracked instrument includes receiving the first image from the imaging device.

(102) At block **1935**, processing circuitry **3320** rotates the imaging device (including the emitter and the detector). In some examples, the imaging device includes a C-arm or an O-arm imaging device.

(103) At block **1940**, processing circuitry **3320** determines a second virtual position of the emitter. In some embodiments, determining the second virtual position of the emitter includes receiving the second virtual position from a tracking system.

(104) At block **1945**, processing circuitry **3320** determines a second virtual position of the detector. In some embodiments, determining the second virtual position of the detector includes receiving the second virtual position from a tracking system.

(105) At block **1950**, processing circuitry **3320** determines a second virtual position of the tracked instrument while the tracked instrument is at a second physical position between the emitter and the detector. In some embodiments, determining the second virtual position of the tracked instrument includes receiving the second virtual position from a tracking system.

(106) In additional or alternative embodiments, the first virtual position of the tracked instrument is the second virtual position of the tracked instrument. For example, the imaging device can include at least one of a C-arm and a O-arm and responsive to obtaining the first image, the imaging device can be rotated (block **1935**) such that the second virtual position of the emitter is different than the first virtual position of the emitter and that the second virtual position of the detector is different than the first virtual position of the detector. As a result an image of the tracked instrument from a different perspective can be taken without moving the tracked instrument.

(107) In additional or alternative embodiments, the first virtual position of the tracked instrument is different than the second virtual position of the tracked instrument. The first virtual position of the emitter is the second virtual position of the emitter The first virtual position of the detector is the second virtual position. For example, without rotating the imaging device an image of the tracked instrument can be taken from a different perspective by moving the tracked instrument.

(108) At block **1955**, processing circuitry **3320** determines a second expected image of the tracked instrument. In some embodiments, the second expected image of the tracked instrument is determined by simulating operation of the emitter and the detector based on the second virtual position of the emitter, the second virtual position of the detector, the second virtual position of the tracked instrument, and a predetermined shape of the tracked instrument.

(109) At block **1960**, processing circuitry **3320** obtains a second image of the tracked instrument. In

some embodiments, obtaining the second image of the tracked instrument includes receiving the second image from the imaging device.

(110) At block **1965**, processing circuitry **3320** determines whether the tracked instrument is accurate based on the first expected image, the second expected image, the first image, and the second image. In some embodiments, the first expected image, the second expected image, the first image, and the second image each include an image of the tip of the tracked instrument.

(111) At block **1970**, processing circuitry **3320** performs an action based on whether the tracked instrument is accurate. In some embodiments, determining whether the tracked instrument is accurate includes determining that a difference between the first expected image and/or the second expected image and the first image and/or the second image exceeds a predetermined threshold. In some examples, performing the action includes outputting an indication that the tracked instrument is not suitable for use. In additional or alternative examples, performing the action includes calibrating a tracking system used to track the tracked instrument using at least one of the first expected image, the second expected image, the first image, and the second image.

(112) Various operations of FIG. **19** may be optional. For example, blocks **1935**, **1940**, **1945**, and **1970** may be optional in some embodiments.

(113) Embodiments that include performing an accuracy check and/or calibrating a tracked instrument based on comparison of an actual position with an expected position on a display device are described below.

(114) In some embodiments, a display screen is available to show tracked instruments. In some examples, the display screen is near the surgical area and is already covered with sterile drape. The screen may be large size (e.g., 22 inches or larger). A reference element can be coupled to the display screen to allow it to be tracked by a navigation camera. A large reference element array can yield improved accuracy of tracking and, in some examples, due to the large physical size, more than four optical markers can be used to improve the fidelity of tracking.

(115) In additional or alternative embodiments, when a user brings a navigated instrument near the display screen, its position with respect to the reference element on the display screen is calculated. The theoretical position of the tracked tip of the instrument CAD is then shown on the display screen. The user can visually compare the accuracy of the physical position of the instrument tip with the position displayed on the screen. With aid of a virtual measurement tool, the user can then assess the accuracy.

(116) FIG. **17** illustrates an example of a display device **1710** displaying a theoretical position (front view **1730** and side view **1740**) of the tip of a tracked instrument **1750**. The display device **1710** has reference elements **1720** and the tracked instrument **1750** has reference elements **1760** for being tracked by a navigation camera.

(117) In this example, the front view **1730** of the theoretical position of the tip of the tracked instrument **1750** is shown as a hollow triangle on the right half of the screen. The left half of the screen shows a side view **1740** of the theoretical position of the tip of the tracked instrument **1750**, allowing assessment of theoretical height above the screen of the tracked instrument **1750**.

(118) In some embodiments, the display device can be used for performing an accuracy check of any shape of tracked instrument tip. Even unconventional tips, such as a hook can be easily visualized on the screen.

(119) In additional or alternative embodiments, the same display screen can be used for an accuracy check of multiple instruments. In additional or alternative embodiments, the screen array is unlikely to be damaged during surgery due to splatter of blood or other smudges, since it is typically much farther from the surgical field compared to tracked instruments.

(120) In additional or alternative embodiments, if the surface of the display screen can sense the touch of the instrument tip, the accuracy can be calculated as well instead of relying on visual assessment.

(121) In some embodiments, using the display device to perform an accuracy check of a tracked

instrument can improve fidelity of reference element array used for accuracy check and consistency of accuracy checks.
(122) In additional or alternative embodiments, using the display device to perform an accuracy check of a tracked instrument can improve accuracy check workflow for instruments without a sharp, straight tip.
(123) In additional or alternative embodiments, using the display device to perform an accuracy check of a tracked instrument can allow user for visual inspection and assessment of accuracy.
(124) FIG. **20** illustrates an example of operations performed by a system to perform an accuracy check and/or calibration of a tracked instrument based on displaying a virtual position of the tracked instrument on a display device. Although the operations are described below as being performed by the accuracy and calibration module **3300**, any suitable system (e.g., an imaging system or a tracking system) can perform these operations.
(125) At block **2010**, processing circuitry **3320** determines a virtual position of a tracked instrument relative to a display device.
(126) At block **2020**, processing circuitry **3320** displays an indication of the virtual position of the tracked instrument on the display device. In some embodiments, the processing circuitry determines an intended shape of the tracked instrument. For example, an accurate and/or undamaged shape of the tracked instrument. Displaying the indication of the virtual position of the tracked instrument includes: displaying on a first part of the display device, a first portion of the intended shape of the tracked instrument in a front view perspective based on the virtual position of the tracked instrument; and displaying on a second part of the display device, a second portion of the tracked instrument in a side view perspective based on the virtual position of the tracked instrument.
(127) At block **2030**, processing circuitry **3320** receives an indication of an actual position of the tracked instrument relative to the display device. In some embodiments, receiving the actual position of the tracked instrument includes receiving an indication from a user.
(128) At block **2040**, processing circuitry **3320** determines whether the tracked instrument is accurate based on the indication of the actual position relative to the virtual position of the tracked instrument.
(129) At block **2050**, processing circuitry **3320** performs an action based on whether the tracked instrument is accurate. In some embodiments, performing the action includes, responsive to determining whether the tracked instrument is accurate, outputting an indication of whether the tracked instrument is suitable for use. In additional or alternative embodiments, performing the action includes, responsive to determining whether the tracked instrument is accurate, calibrating a tracking system used to track the tracked instrument using at least one of the virtual position of the tracked instrument and the actual position of the tracked instrument.
(130) Various operations of FIG. **20** may be optional. For example, block **2050** may be optional in some embodiments.
Further Definitions and Embodiments
(131) In the above-description of various embodiments of present inventive concepts, it is to be understood that the terminology used herein is for the purpose of describing particular embodiments only and is not intended to be limiting of present inventive concepts. Unless otherwise defined, all terms (including technical and scientific terms) used herein have the same meaning as commonly understood by one of ordinary skill in the art to which present inventive concepts belongs. It will be further understood that terms, such as those defined in commonly used dictionaries, should be interpreted as having a meaning that is consistent with their meaning in the context of this specification and the relevant art and will not be interpreted in an idealized or overly formal sense expressly so defined herein.
(132) When an element is referred to as being “connected”, “coupled”, “responsive”, or variants thereof to another element, it can be directly connected, coupled, or responsive to the other element

or intervening elements may be present. In contrast, when an element is referred to as being "directly connected", "directly coupled", "directly responsive", or variants thereof to another element, there are no intervening elements present. Like numbers refer to like elements throughout. Furthermore, "coupled", "connected", "responsive", or variants thereof as used herein may include wirelessly coupled, connected, or responsive. As used herein, the singular forms "a", "an" and "the" are intended to include the plural forms as well, unless the context clearly indicates otherwise. Well-known functions or constructions may not be described in detail for brevity and/or clarity. The term "and/or" includes any and all combinations of one or more of the associated listed items.

(133) It will be understood that although the terms first, second, third, etc. may be used herein to describe various elements/operations, these elements/operations should not be limited by these terms. These terms are only used to distinguish one element/operation from another element/operation. Thus, a first element/operation in some embodiments could be termed a second element/operation in other embodiments without departing from the teachings of present inventive concepts. The same reference numerals or the same reference designators denote the same or similar elements throughout the specification.

(134) As used herein, the terms "comprise", "comprising", "comprises", "include", "including", "includes", "have", "has", "having", or variants thereof are open-ended, and include one or more stated features, integers, elements, steps, components or functions but does not preclude the presence or addition of one or more other features, integers, elements, steps, components, functions or groups thereof. Furthermore, as used herein, the common abbreviation "e.g.", which derives from the Latin phrase "exempli gratia," may be used to introduce or specify a general example or examples of a previously mentioned item, and is not intended to be limiting of such item. The common abbreviation "i.e.", which derives from the Latin phrase "id est," may be used to specify a particular item from a more general recitation.

(135) Example embodiments are described herein with reference to block diagrams and/or flowchart illustrations of computer-implemented methods, apparatus (systems and/or devices) and/or computer program products. It is understood that a block of the block diagrams and/or flowchart illustrations, and combinations of blocks in the block diagrams and/or flowchart illustrations, can be implemented by computer program instructions that are performed by one or more computer circuits. These computer program instructions may be provided to a processor circuit of a general purpose computer circuit, special purpose computer circuit, and/or other programmable data processing circuit to produce a machine, such that the instructions, which execute via the processor of the computer and/or other programmable data processing apparatus, transform and control transistors, values stored in memory locations, and other hardware components within such circuitry to implement the functions/acts specified in the block diagrams and/or flowchart block or blocks, and thereby create means (functionality) and/or structure for implementing the functions/acts specified in the block diagrams and/or flowchart block(s).

(136) These computer program instructions may also be stored in a tangible computer-readable medium that can direct a computer or other programmable data processing apparatus to function in a particular manner, such that the instructions stored in the computer-readable medium produce an article of manufacture including instructions which implement the functions/acts specified in the block diagrams and/or flowchart block or blocks. Accordingly, embodiments of present inventive concepts may be embodied in hardware and/or in software (including firmware, resident software, micro-code, etc.) that runs on a processor such as a digital signal processor, which may collectively be referred to as "circuitry," "a module" or variants thereof.

(137) It should also be noted that in some alternate implementations, the functions/acts noted in the blocks may occur out of the order noted in the flowcharts. For example, two blocks shown in succession may in fact be executed substantially concurrently or the blocks may sometimes be executed in the reverse order, depending upon the functionality/acts involved. Moreover, the

functionality of a given block of the flowcharts and/or block diagrams may be separated into multiple blocks and/or the functionality of two or more blocks of the flowcharts and/or block diagrams may be at least partially integrated. Finally, other blocks may be added/inserted between the blocks that are illustrated, and/or blocks/operations may be omitted without departing from the scope of inventive concepts. Moreover, although some of the diagrams include arrows on communication paths to show a primary direction of communication, it is to be understood that communication may occur in the opposite direction to the depicted arrows.

(138) Many variations and modifications can be made to the embodiments without substantially departing from the principles of the present inventive concepts. All such variations and modifications are intended to be included herein within the scope of present inventive concepts. Accordingly, the above disclosed subject matter is to be considered illustrative, and not restrictive, and the appended examples of embodiments are intended to cover all such modifications, enhancements, and other embodiments, which fall within the spirit and scope of present inventive concepts. Thus, to the maximum extent allowed by law, the scope of present inventive concepts are to be determined by the broadest permissible interpretation of the present disclosure including the following examples of embodiments and their equivalents, and shall not be restricted or limited by the foregoing detailed description.

Claims

1. A system configured to perform an accuracy check of a tracked surgical instrument, the system comprising: a camera; processing circuitry; wherein the camera is coupled to the processing circuitry; and memory coupled to the processing circuitry and having instructions stored therein that are executable by the processing circuitry to cause the system to perform operations including: determining information about a shape of a touch sensor relative to a reference element coupled to the touch sensor; capturing, via the camera, an image of the reference element coupled to the touch sensor; determining a virtual position of the reference element coupled to the touch sensor based on the image of the reference element coupled to the touch sensor, the virtual position of the reference element coupled to the touch sensor including a virtual location and a virtual pose of the reference element coupled to the touch sensor; determining a virtual position within a virtual space of the touch sensor based on the information about the shape of the touch sensor and the virtual position of the reference element coupled to the touch sensor, the virtual position of the touch sensor including a virtual location and a virtual pose of the touch sensor; determining information about a shape of the tracked surgical instrument relative to a reference element coupled to the tracked surgical instrument; capturing, via the camera, an image of the reference element coupled to the tracked surgical instrument; determining a virtual position of the reference element coupled to the tracked surgical instrument based on the image of the reference element coupled to the tracked surgical instrument, the virtual position of the reference element coupled to the tracked surgical instrument including a virtual location and a virtual pose of the reference element coupled to the tracked surgical instrument; determining a virtual position within the virtual space of the tracked surgical instrument based on the shape of the tracked surgical instrument and the reference element coupled to the tracked surgical instrument, the virtual position of the tracked surgical instrument including a virtual location and a virtual pose of the tracked surgical instrument; determining a point of contact on the touch sensor between the tracked surgical instrument and the touch sensor; determining an expected point of contact on the touch sensor between the tracked surgical instrument and the touch sensor based on the virtual position of the touch sensor and the virtual position of the tracked surgical instrument; and determining whether the tracked surgical instrument is accurate based on a difference between the point of contact and the expected point of contact.

2. The system of claim 1, wherein determining the information about the shape of the tracked

surgical instrument includes determining an intended position of a tip of the tracked surgical instrument relative to the reference element coupled to the tracked surgical instrument, wherein determining the point of contact on the touch sensor includes determining a point of contact between the tip of the tracked surgical instrument and the touch sensor, and wherein determining the expected point of contact on the touch sensor includes determining a point of contact between the tip of the tracked surgical instrument and the touch sensor based on the virtual position of the touch sensor and the virtual position of the tracked surgical instrument.

3. The system of claim 1, wherein the system comprises: the touch sensor coupled to the processing circuitry, the touch sensor including a touchscreen, wherein determining the point of contact includes detecting a location on the touchscreen that the tracked surgical instrument is touching.

4. The system of claim 3, wherein the touch sensor includes a plurality of touch sensors coupled together to form an opening, and wherein determining the point of contact on the touch sensor includes determining a plurality of points of contact, each point of contact between one of the touch sensors of the plurality of touch sensors and the tracked surgical instrument while the tracked surgical instrument is positioned in the opening.

5. The system of claim 1, wherein determining the point of contact on the touch sensor includes determining a plurality of points of contact between the tracked surgical instrument and the touch sensor, wherein determining the expected point of contact on the touch sensor includes determining a plurality of expected points of contact between the tracked surgical instrument and the touch sensor based on the virtual position of the touch sensor and the virtual position of the tracked surgical instrument, and wherein determining whether the tracked surgical instrument is accurate includes determining whether the tracked surgical instrument is accurate based on a difference between the plurality of points of contact and the plurality of expected points of contact.

6. The system of claim 1, wherein determining whether the tracked surgical instrument is accurate includes determining that the difference exceeds a predetermined threshold, the operations further including: outputting an indication that the tracked surgical instrument is not suitable for use.

7. The system of claim 1, wherein determining whether the tracked surgical instrument is accurate includes determining that the difference exceeds a predetermined threshold, the operations further including: calibrating a tracking system used to track the tracked surgical instrument using at least one of the point of contact, the expected point of contact, and the difference.

8. The system of claim 1, wherein the system comprises: a display device coupled to the processing circuitry, the display device including the touch sensor, the operations further including: displaying, via the display device, an indication of the expected point of contact, wherein determining the point of contact on the display device between the tracked surgical instrument and the display device includes receiving an indication of the point of contact on the display device from a user.