MEDICAL IMAGING SYSTEMS AND ASSOCIATED DEVICES AND METHODS

Abstract

Systems, methods, and devices for medical imaging are disclosed herein. In some embodiments, a method for imaging an anatomic region includes receiving, from a detector carried by an imaging arm of an x-ray imaging apparatus, a plurality of images of the anatomic region. The images can be obtained during manual rotation of the imaging arm. The imaging arm can be stabilized by a shim structure during the manual rotation. The method can also include receiving, from at least one sensor coupled to the imaging arm, pose data of the imaging arm during the manual rotation. The method can further include generating, based on the images and the pose data, a 3D representation of the anatomic region.

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Background/Summary

CROSS-REFERENCE TO RELATED APPLICATIONS [0001] The present application is a continuation of U.S. patent application Ser. No. 18/823,222, filed Sep. 3, 2024, which is a continuation of U.S. patent application Ser. No. 18/424,006, filed Jan. 26, 2024, now U.S. Pat. No. 12,171,601, issued Dec. 24, 2024, which is a continuation of U.S. patent application Ser. No. 18/459,869, filed Sep. 1, 2023, now U.S. Pat. No. 11,918,395, issued Mar. 5, 2024, which is a continuation of U.S. patent application Ser. No. 18/175,275, filed Feb. 27, 2023, now U.S. Pat. No. 11,786,198, issued Oct. 17, 2023, which is a continuation of U.S. patent application Ser. No. 17/819,811, filed Aug. 15, 2022, now U.S. Pat. No. 11,617,552, issued Apr. 4, 2023, which is a continuation of U.S. patent application Ser. No. 17/658,642, filed Apr. 8, 2022, now U.S. Pat. No. 11,457,883, issued Oct. 4, 2022, which claims the benefit of priority to U.S. Provisional Application No. 63/172,886, filed Apr. 9, 2021; U.S. Provisional Application No. 63/203,270, filed Jul. 15, 2021; and U.S. Provisional Application No. 63/260,241, filed Aug. 13, 2021; each of which is incorporated by reference herein in its entirety.

TECHNICAL FIELD
[0002] The present technology relates generally to medical imaging, and in particular, to systems for generating a three-dimensional (3D) representation of a patient's anatomy and associated methods and devices.
BACKGROUND
[0003] 3D anatomic models, such as computed tomography (CT) volumetric reconstructions, are frequently used in image-guided medical procedures to allow the physician to visualize the patient anatomy in three dimensions and accurately position surgical tools at the appropriate locations. However, 3D models generated from preprocedural image data may not accurately reflect the actual anatomy at the time of the procedure. Moreover, if the model is not correctly registered to the anatomy, it may be difficult or impossible for the physician to navigate the tool to the right location, thus compromising the accuracy and efficacy of the procedure.
[0004] Cone-beam computed tomography (CBCT) has been used to generate high resolution, 3D volumetric reconstructions of a patient's anatomy for image guidance during a medical procedure. However, many physicians do not have ready access to conventional CBCT imaging systems because these systems are extremely expensive and often reserved for use by specialty departments.

While tomosynthesis (also known as limited-angle tomography) has also been used for intraprocedural imaging, this technique is unable to produce 3D reconstructions with sufficiently high resolution for many procedures. Accordingly, improved medical imaging systems and methods are needed.

Description

BRIEF DESCRIPTION OF THE DRAWINGS

[0005] Many aspects of the present disclosure can be better understood with reference to the following drawings. The components in the drawings are not necessarily to scale. Instead, emphasis is placed on clearly illustrating the principles of the present disclosure.

[0006] FIGS. **1**A-**1**E illustrate a system for imaging a patient in accordance with embodiments of the present technology.

[0007] FIGS. **2**A and **2**B illustrate examples of unwanted movements that may occur with a manually-operated imaging apparatus.

[0008] FIGS. **3**A and **3**B illustrate a set of shim structures configured in accordance with embodiments of the present technology.

[0009] FIGS. **3**C and **3**D illustrate shim structures having variable thicknesses in accordance with embodiments of the present technology.

[0010] FIGS. **4**A and **4**B illustrate a set of L-shaped shim structures configured in accordance with embodiments of the present technology.

[0011] FIGS. **4**C and **4**D illustrate an adjustable L-shaped shim structure configured in accordance with embodiments of the present technology.

[0012] FIGS. **5**A and **5**B illustrate a set of U-shaped shim structures configured in accordance with embodiments of the present technology.

[0013] FIGS. **5**C and **5**D illustrate an adjustable U-shaped shim structure configured in accordance with embodiments of the present technology.

[0014] FIGS. **6**A and **6**B illustrate another set of U-shaped shim structures configured in accordance with embodiments of the present technology.

[0015] FIGS. **7**A and **7**B illustrate a shim structure with two arm regions configured in accordance with embodiments of the present technology.

[0016] FIGS. **7**C and **7**D illustrate a shim structure with tapered arm regions configured in accordance with embodiments of the present technology.

[0017] FIG. **7**E illustrates a shim structure including a set of ridges configured in accordance with embodiments of the present technology.

[0018] FIG. **7**F illustrates a shim structure including a plurality of protrusions configured in accordance with embodiments of the present technology.

[0019] FIG. **7**G illustrates a shim structure including a plurality of square or rectangular notches configured in accordance with embodiments of the present technology.

[0020] FIG. **7**H illustrates a shim structure including a plurality of triangular notches configured in accordance with embodiments of the present technology.

[0021] FIGS. **8**A and **8**B illustrate a set of shim structures with rollers configured in accordance with embodiments of the present technology.

[0022] FIGS. **9**A-**9**F illustrate a shim structure with a mounting mechanism configured in accordance with embodiments of the present technology.

[0023] FIGS. **10**A-**10**D illustrate another shim structure with a mounting mechanism configured in accordance with embodiments of the present technology.

[0024] FIG. **11** is a graph illustrating motion of a motion sensor on a C-arm detector with and without shim stabilization.

[0025] FIG. **12** illustrates an example of unwanted movements that may occur with a manually-operated imaging apparatus.

[0026] FIGS. **13**A and **13**B illustrate a lever structure configured in accordance with embodiments of the present technology.

[0027] FIG. **13**C illustrates an adjustable lever structure configured in accordance with embodiments of the present technology.

[0028] FIG. **13**D illustrates another adjustable lever structure configured in accordance with embodiments of the present technology.

[0029] FIGS. **14**A and **14**B illustrate a lever structure in accordance with embodiments of the present technology.

[0030] FIG. **14**C illustrates another lever structure configured in accordance with embodiments of the present technology.

[0031] FIGS. **14**D and **14**E illustrate an adjustable lever structure configured in accordance with embodiments of the present technology.

[0032] FIG. **15** illustrates a motion sensor coupled to an imaging apparatus in accordance with embodiments of the present technology.

[0033] FIG. **16** illustrates a motion sensor and a radiation sensor coupled to an imaging apparatus in accordance with embodiments of the present technology.

[0034] FIGS. **17**A and **17**B illustrate an attachment device configured in accordance with embodiments of the present technology.

[0035] FIG. **17**C illustrates the attachment device of FIGS. **17**A and **17**B coupled to an imaging apparatus, in accordance with embodiments of the present technology.

[0036] FIG. **17**D illustrates another attachment device configured in accordance with embodiments of the present technology.

[0037] FIG. **17**E illustrates another attachment device configured in accordance with embodiments of the present technology.

[0038] FIGS. **18**A and **18**B illustrate a fiducial marker board for pose estimation in accordance with embodiments of the present technology.

[0039] FIG. **18**C illustrates another fiducial marker board in accordance with embodiments of the present technology.

[0040] FIG. **18**D illustrates yet another fiducial marker board in accordance with embodiments of the present technology.

[0041] FIG. **18**E illustrates another fiducial marker board in accordance with embodiments of the present technology.

[0042] FIGS. **18**F and **18**G illustrate a fiducial marker board and a phantom in accordance with embodiments of the present technology.

[0043] FIG. **19** is a flow diagram illustrating a method for operating an imaging apparatus, in accordance with embodiments of the present technology.

[0044] FIG. **20** is a flow diagram illustrating a method for calibrating an imaging apparatus, in accordance with embodiments of the present technology.

[0045] FIGS. **21**A-**21**D illustrate fiducial marker grids for distortion correction in accordance with embodiments of the present technology.

[0046] FIG. **22**A illustrates a fiducial marker phantom for geometric calibration in accordance with embodiments of the present technology.

[0047] FIG. **22**B illustrates another fiducial marker phantom configured in accordance with embodiments of the present technology.

[0048] FIG. **22**C illustrates an assembly that can form part of the fiducial marker phantom of FIG. **22**B, in accordance with embodiments of the present technology.

[0049] FIG. **22**D illustrates another fiducial marker phantom configured in accordance with embodiments of the present technology.

[0050] FIG. **23**A is a flow diagram illustrating a method for imaging an anatomic region, in accordance with embodiments of the present technology.

[0051] FIG. **23**B is a flow diagram illustrating a method for generating a 3D reconstruction, in accordance with embodiments of the present technology.

[0052] FIG. **24** is a flow diagram illustrating a method of preparing an imaging apparatus for image acquisition, in accordance with embodiments of the present technology.

[0053] FIG. **25**A is a flow diagram illustrating a method for calibration and image acquisition using a fiducial marker board in accordance with embodiments of the present technology.

[0054] FIG. **25**B is a flow diagram illustrating a method for operating an imaging apparatus, in accordance with embodiments of the present technology.

[0055] FIG. **26**A is a CBCT image of a phantom generated by a manually-operated imaging apparatus without calibration or shim stabilization.

[0056] FIG. **26**B is a CBCT image of a phantom generated by a manually-operated imaging apparatus with calibration and shim stabilization, in accordance with embodiments of the present technology.

[0057] FIG. **27**A is a CBCT image of a lung generated by a manually-operated imaging apparatus without calibration or shim stabilization.

[0058] FIG. **27**B is a CBCT image of a lung generated by a manually-operated imaging apparatus with calibration and shim stabilization, in accordance with embodiments of the present technology.

[0059] FIG. **27**C is a CBCT image of a lung generated with a robotically-operated CBCT imaging system.

DETAILED DESCRIPTION

[0060] The present technology generally relates to systems, methods, and devices for medical imaging. For example, in some embodiments, the systems and methods described herein use a mobile C-arm x-ray imaging apparatus (also referred to herein as a "mobile C-arm apparatus") to generate a 3D reconstruction of a patient's anatomy using CBCT imaging techniques. Unlike conventional systems and devices that are specialized for CBCT imaging, the mobile C-arm apparatus may lack a motor and/or other automated mechanisms for rotating the imaging arm that carries the x-ray source and detector. Instead, the imaging arm is manually rotated through a series of different angles to obtain a sequence of two-dimensional (2D) projection images of the anatomy. In some situations, the manual rotation may produce undesirable movements of the imaging arm (e.g., oscillations, vibrations, shifting, flexing) that can interfere with the quality of the 3D reconstruction generated from the 2D images. Additionally, the mobile C-arm apparatus may lack sensors for obtaining pose data of the imaging arm during image acquisition, which may be needed for an accurate 3D reconstruction.

[0061] Accordingly, in some embodiments, a method for imaging an anatomic region includes receiving a plurality of 2D images of the anatomic region from a detector carried by an imaging arm of an x-ray imaging apparatus (e.g., a mobile C-arm apparatus). The 2D images can be obtained during manual rotation of the imaging arm. The imaging arm can be stabilized by a shim structure during the manual rotation to reduce or inhibit unwanted movements. The method can also include receiving sensor data indicative of a plurality of poses of the imaging arm during the manual rotation from at least one sensor coupled to the imaging arm (e.g., an inertial measurement unit (IMU)). The method can further include generating a 3D reconstruction of the anatomic region based on the 2D images and the sensor data. The 3D reconstruction can be displayed to a physician or other operator to provide image-based guidance during a medical procedure performed in the anatomic region (e.g., a biopsy or ablation procedure).

[0062] The embodiments described herein can provide many advantages over conventional imaging technologies. For example, the systems and methods herein can use a manually-rotated mobile C-arm apparatus to generate high quality CBCT images of a patient's anatomy, rather than a specialized CBCT imaging system. This approach can reduce costs and increase the availability of

CBCT imaging, thus allowing CBCT imaging techniques to be used in many different types of medical procedures. For example, CBCT imaging can be used to generate intraprocedural 3D models of an anatomic region for guiding a physician in accurately positioning a tool at a target location in the anatomy, e.g., for biopsy, ablation, or other diagnostic or treatment procedures.

[0063] Embodiments of the present disclosure will be described more fully hereinafter with reference to the accompanying drawings in which like numerals represent like elements throughout the several figures, and in which example embodiments are shown. Embodiments of the claims may, however, be embodied in many different forms and should not be construed as limited to the embodiments set forth herein. The examples set forth herein are non-limiting examples and are merely examples among other possible examples.

[0064] As used herein, the terms "vertical," "lateral," "upper," and "lower" can refer to relative directions or positions of features of the embodiments disclosed herein in view of the orientation shown in the Figures. For example, "upper" or "uppermost" can refer to a feature positioned closer to the top of a page than another feature. These terms, however, should be construed broadly to include embodiments having other orientations, such as inverted or inclined orientations where top/bottom, over/under, above/below, up/down, and left/right can be interchanged depending on the orientation.

[0065] Although certain embodiments of the present technology are described in the context of medical procedures performed in the lungs, this is not intended to be limiting. Any of the embodiments disclosed herein can be used in other types of medical procedures, such as procedures performed on or in the musculoskeletal system, vasculature, abdominal cavity, gastrointestinal tract, genitourinary tract, brain, and so on. Additionally, any of the embodiments herein can be used for applications such as surgical tool guidance, biopsy, ablation, chemotherapy administration, surgery, or any other procedure for diagnosing or treating a patient.

[0066] The headings provided herein are for convenience only and do not interpret the scope or meaning of the claimed present technology.

I. Overview of Technology

[0067] Lung cancer kills more people each year than breast, prostate, and colon cancers combined. Most lung cancers are diagnosed at a late stage, which contributes to the high mortality rate. Earlier diagnosis of lung cancer (e.g., at stages 1-2) can greatly improve survival. The first step in diagnosing an early-stage lung cancer is to perform a lung biopsy on the suspicious nodule or lesion. Bronchoscopic lung biopsy is the conventional biopsy route, but typically suffers from poor success rates (e.g., only 50% to 70% of nodules are correctly diagnosed), meaning that the cancer status of many patients remains uncertain even after the biopsy procedure. One common reason for non-diagnostic biopsy is that the physician fails to place the biopsy needle into the correct location in the nodule before collecting the biopsy sample. This situation can occur due to shortcomings of conventional technologies for guiding the physician in navigating the needle to the target nodule. For example, conventional technologies typically use a static chest CT scan of the patient obtained before the biopsy procedure (e.g., days to weeks beforehand) that is registered to the patient's anatomy during the procedure (e.g., via electromagnetic (EM) navigation or shape sensing technologies). Registration errors can cause the physician to completely miss the nodule during needle placement. These errors, also known as CT-to-body divergence, occur when the preprocedural scan data does not match the patient anatomy data obtained during the actual procedure. These differences can occur because the lungs are dynamic and often change in volume from day-to-day and/or when patients are under anesthesia. Research has shown that the average error between the preprocedural CT scan and the patient's anatomy during the procedure is 1.8 cm, which is larger than many of the pulmonary nodules being biopsied.

[0068] CBCT is an imaging technique capable of producing high resolution 3D volumetric reconstructions of a patient's anatomy. For bronchoscopic lung biopsy, intraprocedural CBCT imaging can be used to confirm that the biopsy needle is positioned appropriately relative to the

target nodule and has been shown to increase diagnostic accuracy by almost 20%. A typical CBCT procedure involves scanning the patient's body with a cone-shaped x-ray beam that is rotated over a wide, circular arc (e.g., 180° to 360°) to obtain a sequence of 2D projection images. A 3D volumetric reconstruction of the anatomy can be generated from the 2D images using image reconstruction techniques such as filtered backprojection or iterative reconstruction. Conventional CBCT imaging systems include a motorized imaging arm for automated, highly-controlled rotation of the x-ray source and detector over a smooth, circular arc during image acquisition. These systems are also capable of accurately tracking the pose of the imaging arm across different rotation angles. However, CBCT imaging systems are typically large, extremely expensive, and may not be available to many physicians, such as pulmonologists performing lung biopsy procedures.

[0069] Manually-operated mobile C-arm apparatuses are less expensive and more readily available than specialized CBCT imaging systems, but are generally unsuitable for CBCT imaging for some or all of the following reasons. First, mobile C-arm apparatuses typically lack a motorized imaging arm and thus must be manually rotated during imaging acquisition. However, with manual rotation, it is extremely difficult to produce a smooth, isocentric, circular motion of the imaging arm over sufficiently large angles (e.g., greater than) 90° for CBCT imaging. Due to mechanical instabilities present in many mobile C-arm apparatuses, the imaging arm may exhibit unwanted movements (e.g., oscillations, vibrations, shifts, flexing) during manual rotation, which may cause the imaging arm to move along a non-circular trajectory or otherwise detrimentally affect the quality of the resulting 3D reconstruction. Second, mobile C-arm apparatuses generally lack the capability to accurately determine the pose of the imaging arm as the imaging arm rotates around the patient. In a typical CBCT imaging procedure, hundreds of images are acquired at a rate of 10-50 images per second, and the pose of the imaging arm needs to be determined for each image. Third, mobile C-arm apparatuses often use an image intensifier as the x-ray detector, which can create significant distortion artifacts that prevent accurate image reconstruction. Image intensifiers are also relatively heavy (e.g., hundreds of pounds) and thus may further destabilize the imaging arm during manual rotation.

[0070] Tomosynthesis is a technique that may be used to generate intraprocedural images of patient anatomy. However, because tomosynthesis uses a much smaller rotation angle during image acquisition (e.g., 15° to 70°), the resulting images are typically low resolution, lack sufficient depth information, and/or may include significant distortion. Tomosynthesis is therefore typically not suitable for applications requiring highly accurate 3D spatial information.

[0071] Accordingly, there is a need for imaging techniques that are capable of producing intraprocedural, high resolution 3D representations of a patient's anatomy using low-cost, accessible imaging systems such as mobile C-arm apparatuses. The present technology can address these and other challenges by providing systems, methods, and devices for performing CBCT imaging using a manually-rotated imaging apparatus, also referred to herein as "manually-rotated CBCT" or "mrCBCT." For example, in some embodiments, the systems described herein mechanically stabilize the imaging arm and/or other components of the mobile C-arm apparatus using one or more shim structures (e.g., wedges, blocks, dampers, etc.) that reduce or prevent unwanted movements during manual rotation. The system can also include one or more lever structure (e.g., a detachable or permanently affixed handle) to assist the operator in rotating the imaging arm from locations that are less likely to produce unwanted movements. The system can further include at least one sensor (e.g., a motion sensor such as an IMU) that automatically tracks the pose of the imaging arm during rotation. The sensor data can be temporally synchronized to the obtained 2D projection images to accurately determine the pose of the imaging arm for each image. In some embodiments, the system is calibrated before and/or during use to correct image distortion (e.g., from the image intensifier), determine calibration parameters to compensate for mechanical differences between individual mobile C-arm apparatuses, and/or adjust for variations in how the

operator manually rotates the imaging arm. The approaches described herein can be used to adapt a manually-operated mobile C-arm apparatus for CBCT imaging, thus allowing high quality CBCT reconstructions to be produced using relatively inexpensive and accessible imaging equipment.

II. Medical Imaging Systems and Associated Devices and Methods

[0072] FIG. **1**A is a partially schematic illustration of a system **100** for imaging a patient **102** in accordance with embodiments of the present technology. The system **100** includes an imaging apparatus **104** operably coupled to a console **106**. The imaging apparatus **104** can be any suitable device configured to generate images of a target anatomic region of the patient **102**, such as an x-ray imaging apparatus. In the illustrated embodiment, for example, the imaging apparatus **104** is a mobile C-arm apparatus configured for fluoroscopic imaging. A mobile C-arm apparatus typically includes a manually-movable imaging arm **108** configured as a curved, C-shaped gantry (also known as a "C-arm"). Examples of mobile C-arm apparatuses include, but are not limited to, the OEC 9900 Elite (GE Healthcare) and the BV Pulsera (Philips). In other embodiments, however, the techniques described herein can be adapted to other types of imaging apparatuses **104** having a manually-movable imaging arm **108**, such as a G-arm imaging apparatus.

[0073] The imaging arm **108** can carry a radiation source **110** (e.g., an x-ray source) and a detector **112** (e.g., an x-ray detector such as an image intensifier or flat panel detector). The radiation source **110** can be mounted at a first end portion **114** of the imaging arm **108**, and the detector **112** can be mounted at a second end portion **116** of the imaging arm **108** opposite the first end portion **114**. During a medical procedure, the imaging arm **108** can be positioned near the patient **102** such that the target anatomic region is located between the radiation source **110** and the detector **112**. The imaging arm **108** can be rotated to a desired pose (e.g., angle) relative to the target anatomic region. The radiation source **110** can output radiation (e.g., x-rays) that travels through the patient's body to the detector **112** to generate 2D images of the anatomic region (also referred to herein as "projection images"). The image data can be output as still or video images. In some embodiments, the imaging arm **108** is rotated through a sequence of different poses to obtain a plurality of 2D projection images. The images can be used to generate a 3D representation of the anatomic region (also referred to herein as a "3D reconstruction," "volumetric reconstruction," "image reconstruction," or "CBCT reconstruction"). The 3D representation can be displayed as a 3D model or rendering, and/or as one or more 2D image slices (also referred to herein as "CBCT images" or "reconstructed images").

[0074] In some embodiments, the imaging arm **108** is coupled to a base **118** by a support arm **120**. The base **118** can act as a counterbalance for the imaging arm **108**, the radiation source **110**, and the detector **112**. As shown in FIG. **1**A, the base **118** can be a mobile structure including wheels for positioning the imaging apparatus **104** at various locations relative to the patient **102**. In other embodiments, however, the base **118** can be a stationary structure. The base **118** can also carry various functional components for receiving, storing, and/or processing the image data from the detector **112**, as discussed further below.

[0075] The support arm **120** (also referred to as an "attachment arm" or "pivot arm") can connect the imaging arm **108** to the base **118**. The support arm **120** can be an elongate structure having a distal portion **122** coupled to the imaging arm **108**, and a proximal portion **124** coupled to the base **118**. Although the support arm **120** is depicted in FIG. **1**A as being an L-shaped structure ("L-arm") having a vertical section and a horizontal section, in other embodiments the support arm **120** can have a different shape (e.g., a curved shape).

[0076] The imaging arm **108** can be configured to rotate in multiple directions relative to the base **118**. For example, FIG. **1**B is a partially schematic illustration of the imaging apparatus **104** during an orbital rotation. As shown in FIG. **1**B, during an orbital rotation, the imaging arm **108** rotates relative to the support arm **120** and base **118** along a lengthwise direction as indicated by arrows **136**. Thus, during an orbital rotation, the motion trajectory can be located primarily or entirely within the plane of the imaging arm **108**. The imaging arm **108** can be slidably coupled to the

support arm **120** to allow for orbital rotation of the imaging arm **108**. For example, the imaging arm **108** can be connected to the support arm **120** via a first interface **126** that allows the imaging arm **108** to slide along the support arm **120**.

[0077] FIG. **1**C is a perspective view of the first interface **126**, and FIG. **1**D is a partially schematic cross-sectional view of the first interface **126** along axis A-A in FIG. **1**B. Referring to FIGS. **1**C and **1**D together, the imaging arm **108** can include a pair of rails **138** and a recessed track **140** between the rails **138**. The rails **138** can be located at opposite sides (e.g., a first side **142** and a second side **144**) of the first interface **126**. The distal portion **122** of the support arm **120** can fit between the rails **138** and at least partially into the track **140**. The rails **138**, track **140**, and distal portion **122** can collectively form the first interface **126**. As best seen in FIG. **1**D, the distal portion **122** can include a pair of grooves or notches **146** that engage the rails **138** to secure the distal portion **122** to the track **140**. The distal portion **122** can also include one or more wheels or rollers **148** that contact the inner surface of the track **140** so that the imaging arm **108** can slide smoothly relative to the support arm **120** during orbital rotation.

[0078] FIG. **1**E is a partially schematic illustration of the imaging apparatus **104** during a propeller rotation (also known as "angular rotation" or "angulation"). As shown in FIG. **1**E, during a propeller rotation, the imaging arm **108** and support arm **120** rotate relative to the base **118** in a lateral direction as indicated by arrows **150**. The support arm **120** can be rotatably coupled to the base **118** via a second interface **128** (e.g., a pivoting joint or other rotatable connection) that allows the imaging arm **108** and support arm **120** to turn relative to the base **118**. Optionally, the imaging apparatus **104** can include a locking mechanism to prevent orbital rotation while the imaging arm **108** is performing a propeller rotation, and/or to prevent propeller rotation while the imaging arm **108** is performing an orbital rotation.

[0079] Referring again to FIG. **1**A, the imaging apparatus **104** can optionally be configured to rotate in other directions, alternatively or in addition to orbital rotation and/or propeller rotation. For example, in some embodiments, the imaging arm **108** and the distal portion **122** of the support arm **120** are rotatable relative to the rest of the support arm **120** and the base **118** (also known as "flip-flop" rotation). A flip-flop rotation may be advantageous in some situations for reducing interference with other components located near the operating table **152** (e.g., a surgical robotic assembly).

[0080] The imaging apparatus **104** can be operably coupled to a console **106** for controlling the operation of the imaging apparatus **104**. As shown in FIG. **1**A, the console **106** can be a mobile structure with wheels, thus allowing the console **106** to be moved independently of the imaging apparatus **104**. In other embodiments, however, the console **106** can be a stationary structure. The console **106** can be attached to the imaging apparatus **104** by wires, cables, etc., or can be a separate structure that communicates with the imaging apparatus **104** via wireless communication techniques. The console **106** can include a computing device **130** (e.g., a workstation, personal computer, laptop computer, etc.) including one or more processors and memory configured to perform various operations related to image acquisition and/or processing. For example, the computing device **130** can perform some or all of the following operations: receive, organize, store, and/or process data (e.g., image data, sensor data, calibration data) relevant to generating a 3D reconstruction; execute image reconstruction algorithms; execute calibration algorithms; and post-process, render, and/or display the 3D reconstruction. Additional examples of operations that may be performed by the computing device **130** are described in greater detail elsewhere herein.

[0081] The computing device **130** can receive data from various components of the system **100**. For example, the computing device **130** can be operably coupled to the imaging apparatus **104** (e.g., to radiation source **110**, detector **112**, and/or base **118**) via wires and/or wireless communication modalities (e.g., Bluetooth, WiFi) so that the computing device **130** can transmit commands to the imaging apparatus **104** and/or receive data from the imaging apparatus **104**. In some embodiments, the computing device **130** transmits commands to the imaging apparatus **104**

to cause the imaging apparatus **104** to start acquiring images, stop acquiring images, adjust the image acquisition parameters, and so on. The imaging apparatus **104** can transmit image data (e.g., the projection images acquired by the detector **112**) to the computing device **130**. The imaging apparatus **104** can also transmit status information to the computing device **130**, such as whether the components of the imaging apparatus **104** are functioning properly, whether the imaging apparatus **104** is ready for image acquisition, whether the imaging apparatus **104** is currently acquiring images, etc.

[0082] Optionally, the computing device **130** can also receive other types of data from the imaging apparatus **104**. In the embodiment of FIG. **1**A, for example, the imaging apparatus **104** includes at least one sensor **154** configured to generate sensor data indicative of a pose of the imaging arm **108**. The sensor data can be transmitted to the computing device **130** via wired or wireless communication for use in the image processing techniques described herein. Additional details of the configuration and operation of the sensor **154** are provided below.

[0083] The console **106** can include various user interface components allowing an operator (e.g., a physician, nurse, technician, or other healthcare professional) to interact with the computing device **130**. For example, the operator can input commands to the computing device **130** via a suitable input device (e.g., a keyboard, mouse, joystick, touchscreen, microphone). The console **106** can also include a display **132** (e.g., a monitor or touchscreen) for outputting image data, sensor data, reconstruction data, status information, control information, and/or any other suitable information to the operator. Optionally, the base **118** can also include a secondary display **134** for outputting information to the operator.

[0084] Although FIG. **1**A shows the console **106** as being separate from the imaging apparatus **104**, in other embodiments the console **106** can be physically connected to the imaging apparatus **104** (e.g., to the base **118**), such as by wires, cables, etc. Additionally, in other embodiments, the base **118** can include a respective computing device and/or input device, such that the imaging apparatus **104** can also be controlled from the base **118**. In such embodiments, the computing device located in the base **118** can be configured to perform any of the image acquisition and/or processing operations described herein. Optionally, the console **106** can be integrated with the base **118** (e.g., the computing device **130** is located in the base **118**) or omitted altogether such that the imaging apparatus **104** is controlled entirely from the base **118**. In some embodiments, the system **100** includes multiple consoles **106** (e.g., at least two consoles **106**), each with a respective computing device **130**. Any of the processes described herein can be performed on a single console **106** or across any suitable combination of multiple consoles **106**.

A. Stabilization Devices and Methods

[0085] Referring again to FIG. **1**A, the system **100** can be used to perform an imaging procedure in which an operator manually rotates the imaging arm **108** during imaging acquisition, such as an mrCBCT procedure. In such embodiments, the imaging apparatus **104** can be a manually-operated device that lacks any motors or other actuators for automatically rotating the imaging arm **108**. For example, one or both of the first interface **126** and second interface **128** can lack any automated mechanism for actuating orbital rotation and propeller rotation of the imaging arm **108**, respectively. Instead, the user manually applies the rotational force to the imaging arm **108** and/or support arm **120** during the mrCBCT procedure.

[0086] In some embodiments, the imaging procedure involves performing a propeller rotation of the imaging arm **108**. Propeller rotation may be advantageous for mrCBCT or other imaging techniques that involve rotating the imaging arm **108** over a relatively large rotation angle. For example, a mrCBCT or similar imaging procedure can involve rotating the imaging arm **108** over a range of at least 90°, 100°, 110°, 120°, 130°, 140°, 150°, 160°, 170°, 180°, 190°, 200°, 210°, 220°, 230°, 240°, 250°, 260°, 270°, 280°, 290°, 300°, 310°, 320°, 330°, 340°, 350°, or 360°. The total rotation can be within a range from 90° to 360°, 90° to 270°, 90° to 180°, 120° to 360°, 120° to 270°, 120° to 180°, 180° to 360°, or 180° to 270°. As previously discussed, the large rotation angle

may be required for capturing a sufficient number of images from different angular or rotational positions to generate an accurate, high resolution 3D reconstruction of the anatomy. In many situations, it is not possible to achieve such large rotation angles using orbital rotation. For example, as shown in FIG. **1**A, if the imaging apparatus **104** is positioned at one end of the patient's body (e.g., near the head and/or torso of the patient **102**), the orbital rotation of the imaging arm **108** may be constrained by the location of the patient **102** and/or the operating table **152** to a relatively limited rotation angle (e.g., less than) 90°.

[0087] Larger rotation angles can be achieved with propeller rotation, even in the configuration shown in FIG. **1**A. However, propeller rotation can be less mechanically stable than orbital rotation, particularly when the rotational force is applied manually. Accordingly, in the absence of stabilization mechanisms (e.g., when shim structures **156** are omitted), the imaging arm **108** may exhibit unwanted movements during a manual propeller rotation that can detrimentally affect the quality of the resulting CBCT reconstruction. Examples of unwanted movements that can occur include, but are not limited to, oscillations, vibrations, sudden shifts, flexing, and/or other non-uniform motions that cause the imaging arm **108** to deviate from the desired trajectory (e.g., a smooth, single plane, isocentric, and/or circular trajectory). Unwanted movements can occur, for example, due to mechanical instability of the imaging apparatus **104** such as a weight imbalance between the radiation source **110** and detector **112**, as well as mechanical laxity in the first interface **126** and/or second interface **128**. In some embodiments, the detector **112** is much heavier than the radiation source **110** (e.g., an image intensifier can weigh hundreds of pounds). As a result, during propeller rotation, the imaging arm **108** can shift with respect to the support arm **120**, and/or the support arm **120** can shift with respect to the base **118**. Such movements can cause the center of rotation of the imaging arm **108** to move during image acquisition, which can cause the projection images obtained by the detector **112** to be misaligned. The 3D reconstruction produced from such misaligned projection images may include significant image artifacts and/or may lack sufficient spatial resolution for use in many medical procedures.

[0088] FIGS. **2**A and **2**B illustrate examples of unwanted movements that may occur at the first interface **126** during a manual propeller rotation of the imaging arm **108**, in the absence of stabilization mechanisms. Referring to FIGS. **2**A and **2**B together, the first interface **126** can include spaces, gaps, etc., between the various components of the imaging arm **108** and support arm **120** (e.g., between the rails **138**, track **140**, distal portion **122**, grooves **146**, and/or wheels **148**). This mechanical laxity can allow the imaging arm **108** and support arm **120** to shift relative to each other, even when the imaging arm **108** is locked to prevent orbital rotation. For example, the first and second sides **142**, **144** of the first interface **126** can each include a first gap **202**, second gap **204**, and/or third gap **206**. The gaps **202-204** can be located between the rail **138** of the imaging arm **108** and the groove **146** in the distal portion **122** of the support arm **120** (in FIGS. **2**A and **2**B, the gaps **202-204** are labeled only on the second side **144** merely for purposes of simplicity). In the illustrated embodiment, the first gap **202** is between a lower surface of the rail **138** and an upper surface of the groove **146** and, the second gap **204** is between a lateral surface of the rail **138** and a lateral surface of the groove **146**, and the third gap **206** is between a lower surface of the rail **138** and an upper surface of the groove **146**. Due to the presence of the gaps **202-206**, the imaging arm **108** can shift in a vertical direction **208** (FIG. **2**A) and/or a lateral direction **210** (FIG. **2**B) relative to the support arm **120**.

[0089] Referring again to FIG. **1**A, in some embodiments, the system **100** includes features for reducing or preventing unwanted movements that may occur during a mrCBCT procedure. For example, the system **100** can include one or more shim structures **156** for mechanically stabilizing certain portions of the imaging apparatus **104** (the shim structures **156** are omitted in FIGS. **1**B-**1**E merely for purposes of simplicity). The shim structures **156** can be removable or permanent components that are coupled to the imaging apparatus **104** at one or more locations to reduce or prevent unwanted movements during a manual rotation. In the illustrated embodiment, the system

100 includes two shim structures **156** positioned at opposite ends of the first interface **126** between the imaging arm **108** and the support arm **120**. Optionally, the system **100** can include four shim structures **156**, one at each end of the first interface **126** and on both sides **142**, **144** of the first interface **126**. Alternatively or in combination, the system **100** can include one or more shim structures **156** at other locations of the imaging apparatus **104** (e.g., at the second interface **128**). Any suitable number of shim structures **156** can be used, such as one, two, three, four, five, six, seven, eight, nine, ten, 11, 12, or more shim structures.

[0090] The shim structures **156** disclosed herein can make it easier for a user to produce a smooth, uniform movement of the imaging arm **108** over a wide rotation angle without using motors or other automated actuation mechanisms. Accordingly, the projection images generated by the detector **112** can exhibit significantly reduced misalignment compared to projection images generated without the shim structures **156**, thus improving the accuracy and resolution of the resulting 3D reconstruction. The shim structures **156** can also produce a more consistent rotation path of the imaging arm **108**, which can significantly improve the accuracy of the calibration processes disclosed herein. Additional examples and features of shim structures **156** that can be used with the imaging apparatus **104** are described in greater detail below in connection with FIGS. **3**A-**10**D.

[0091] FIGS. **3**A-**10**D illustrate representative examples of shim structures that can be used to stabilize an imaging apparatus, in accordance with embodiments of the present technology. Although the shim structures of FIGS. **3**A-**10**D are described and illustrated with reference to components of the imaging apparatus **104** of FIG. **1**A, it will be appreciated that the shim structures can also be used with other imaging apparatuses and systems. Additionally, any of the features of the shim structures of FIGS. **3**A-**10**D can be combined with each other.

[0092] FIG. **3**A is a partially schematic cross-sectional view of the first interface **126** with a set of shim structures **302***a*, **302***b* configured in accordance with embodiments of the present technology. Referring first to FIG. **3**A, the shim structures **302***a*, **302***b* can be used to stabilize the first interface **126** between the imaging arm **108** and support arm **120** of the imaging apparatus **104**. In the illustrated embodiment, the shim structures **302***a*, **302***b* are positioned at the first and second sides **142**, **144**, respectively, of the first interface **126**. The shim structures **302***a*, **302***b* can fit within the first gaps **202** between the imaging arm **108** and the support arm **120**. The shim structures **302***a*, **302***b* can partially or completely fill the first gaps **202**, thus inhibiting or reducing unwanted movement of the imaging arm **108** relative to the support arm **120** when the imaging arm **108** is manually rotated. In some embodiments, the shim structures **302***a*, **302***b* are removable components that are temporarily inserted into the first interface **126** to stabilize the imaging arm **108** and support arm **120** during manual operation. The shim structures **302***a*, **302***b* can be held in place by friction and/or mechanical interference, or by other mechanisms. In other embodiments, however, the shim structures **302***a*, **302***b* can be permanently affixed within the first interface **126**.

[0093] FIG. **3**B is a perspective view of an individual shim structure **302***a*. The shim structure **302***a* can be an elongate member (e.g., a block, wedge, panel) configured to fill a space between the imaging arm **108** and the support arm **120**. The shim structure **302***a* can be made of any material suitable for dampening, obstructing, or otherwise preventing movement of the imaging arm **108** relative to the support arm **120**, including rigid or compliant materials. The geometry of the shim structure **302***a* can also be varied as desired. In the illustrated embodiment, for example, the shim structure **302***a* has a rectangular shape. In other embodiments, the shim structure **302***a* can have any other suitable shape, such as square, trapezoidal, triangular, circular, oval, etc. The dimensions of the shim structure **302***a* can be configured to provide a desired fit between the imaging arm **108** and the support arm **120**. For example, the shim structure **302***a* can have a length L_1 within a range from 1 cm to 20 cm, a width W_1 within a range from 0.3 cm to 5 cm, and a thickness T_1 within a range from 1 mm to 15 mm. The thickness T_1 can be equal or approximately equal to the height of the first gap **202** (FIG. **3**A), and the length L_1 and width W_1 can be

greater than or equal to the lateral dimensions of the first gap **202**.

[0094] The shim structure **302***b* can be identical or generally similar to the shim structure **302***a*. For example, the shim structures **302***a*, **302***b* can both have the same geometry (e.g., size, shape). In other embodiments, however, the shim structure **302***b* can have a different geometry than the shim structure **302***a*, e.g., the shim structure **302***b* can be larger or smaller than the shim structure **302***a*, can have a different shape than the shim structure **302***a*, etc. Optionally, either the shim structure **302***a* or shim structure **302***b* can be omitted, such that only one of the sides of the first interface **126** includes a shim structure.

[0095] FIG. **3**C is a side view of a shim structure **302***c* having a variable thickness T.sub.2, in accordance with embodiments of the present technology. The shim structure **302***c* can be generally similar to the shim structure **302***a* and/or shim structure **302***b*, except that the thickness T.sub.2 of the shim structure **302***c* decreases along the length L**2** of the shim structure **302***c*, such that the shim structure **302***c* is thicker at a first end region **304** and thinner at a second end region **306**. In the illustrated embodiment, for example, the shim structure **302***c* has a triangular cross-sectional shape, with the angle of the shim structure **302***c* at the second end region **306** being less than or equal to 80°, 70°, 60°, 50°, 45°, 40°, 35°, 30°, 25°, 20°, 15°, 10°, or 5°.

[0096] FIG. **3**D is a partially schematic side view of a set of shim structures **302***c*, **302***c* positioned at the first interface **126** in accordance with embodiments of the present technology. In the illustrated embodiment, the shim structure **302***d* has tapered, wedge-like shape identical or similar to the shim structure **302***c*. In other embodiments, however, either or both of the shim structures **302***c*, **302***d* can be replaced with a shim structure having a different shape, such as the rectangular shape of the shim structure **302***a* of FIG. **3**B. As shown in FIG. **3**D, the shim structures **302***c*, **302***d* can be inserted into the spaces at the first and second ends **308**, **310**, respectively, of the first interface **126** between the distal portion **122** of the support arm **120** and the imaging arm **108**. Although FIG. **3**D shows two shim structures **302***c*, **302***d*, in some embodiments, the first interface **126** can include a total of four shim structures: two shim structures at both sides **142**, **144** of the first end **308**, and two shim structures at both sides **142**, **144** of the second end **310**.

[0097] FIG. **4**A is a partially schematic cross-sectional view of the first interface **126** with a set of L-shaped shim structures **402***a*, **402***b*, and FIG. **4**B is a perspective view of an individual shim structure **402***a*, in accordance with embodiments of the present technology. Referring to FIGS. **4**A and **4**B together, the shim structures **402***a*, **402***b* can be inserted between the imaging arm **108** and the support arm **120** at the first and second sides **142**, **144** of the first interface **126**, respectively. The shim structures **402***a*, **402***b* can each include a first panel **404** connected to a second panel **406** to form an L-shaped structure. The first panel **404** and second panel **406** can fit in the first gap **202** and second gap **204**, respectively, between the imaging arm **108** and the support arm **120**. The first and second panels **404**, **406** can be integrally formed with each other as a single unitary component, or can be separate components that are coupled to each other via adhesives, bonding, fasteners, etc. In the illustrated embodiment, the first and second panels **404**, **406** are connected in a fixed geometry and are not movable relative to each other. In other embodiments, however, the first and second panels **404**, **406** can be movably coupled to each other, as described further below.

[0098] The first and second panels **404**, **406** can each be flattened, elongate members having a geometry (e.g., size, shape) selected to conform to the shape of the first and second gaps **202**, **204**. For example, the angle between the first and second panels **404**, **406** can be greater than or equal to 10°, 20°, 30°, 40°, 45°, 50°, 60°, 70°, 80°, 90°, 100°, 110°, 120°, 130°, 140°, 150°, 160°, or 170°. The first and second panels **404**, **406** can each have any suitable shape, such as rectangular, square, etc. The dimensions of the first and second panels **404**, **406** can also be varied as desired. In the illustrated embodiment, for example, the first and second panels **404**, **406** have the same length L**3** (e.g., within a range from 1 cm to 20 cm) and thickness T.sub.3 (e.g., within a range from 1 mm to 15 mm), but have different widths W.sub.3 and W.sub.4, respectively. The width W.sub.3 of the first panel **404** can be greater than the width W.sub.4 of the second panel **406**. For example, the

width W.sub.3 can be within a range from 0.3 cm to 5 cm, and the width W.sub.4 can be within a range from 0.1 cm to 3 cm. In other embodiments, however, the width W.sub.3 of the first panel **404** can be less than or equal to the width W.sub.4 of the second panel **406**. The first and second panels **404**, **406** can also have different lengths and/or thicknesses. Additionally, although the first and second panels **404**, **406** are both depicted as having a uniform thickness T.sub.3, in other embodiments, the first and/or second panels **404**, **406** can instead have a variable thickness (e.g., a tapered thickness similar to the shim structure **302***c* of FIG. **3**C).

[0099] FIGS. **4**C and **4**D are perspective views of an adjustable L-shaped shim structure **402***c* configured in accordance with embodiments of the present technology. The shim structure **402***c* includes a first panel **408** and a second panel **410** connected to each other via an adjustable connection **412**. In the illustrated embodiment, the first and second panels **408**, **410** each have a rectangular or square flattened section **414** connected to a tapered section **416**. In other embodiments, the first and/or second panels **408**, **410** can have a different shape, as discussed elsewhere herein. For example, the first panel **408** and second panel **410** can be identical or similar to the first panel **404** and second panel **406** of FIGS. **4**A and **4**B, respectively.

[0100] The adjustable connection **412** can be any attachment mechanism (e.g., joint, hinge, pivot, etc.) that allows the first and second panels **408**, **410** to move (e.g., translate and/or rotate) independently relative to each other. For example, as shown in FIGS. **4**C and **4**D, the adjustable connection **412** can be a slidable connection that allows the first and second panels **408**, **410** to slide relative to each other along a lengthwise direction **418**. In some embodiments, the adjustable connection **412** is configured similarly to a sliding dovetail connection and includes a rod or bolt on the edge of one panel (e.g., the first panel **408**) that slides within a receptacle or groove on the edge of the other panel (e.g., the second panel **410**). The adjustable connection **412** can allow the first and second panels **408**, **410** to slide relative to each other for a predetermined distance (e.g., a distance within a range from 3 cm to 5 cm). The adjustable connection **412** can include a hard stop to prevent the first and second panels **408**, **410** from moving beyond the predetermined distance and/or completely separating from each other.

[0101] During use, the adjustable connection **412** allows the first and second panels **408**, **410** to be moved independently to provide an improved fit with the first interface **126** (FIG. **4**A). For example, the first and second panels **408**, **410** can be sequentially inserted into the first gap **202** and second gap **204**, respectively, of the first interface **126**. In some embodiments, the shim structure **402***c* is initially placed in a partially separated configuration as shown in FIG. **4**C, with the second panel **410** displaced vertically relative to the first panel **408**. The first panel **408** can be inserted into the first gap **202** between the imaging arm **108** and the support arm **120**. Next, the second panel **410** can be moved downward and into alignment with the first panel **408** as shown in FIG. **4**D, until the second panel **410** fits into the second gap **204** between the imaging arm **108** and support arm **120**. Alternatively, the order can be reversed, with the second panel **410** being inserted before the first panel **408**. The adjustable connection **412** can allow each panel to be advanced independently to the appropriate insertion depth for stabilization, which can be advantageous in situations where different spaces within the first interface **126** have different dimensions.

[0102] FIG. **5**A is a partially schematic cross-sectional view of the first interface **126** with a set of U-shaped shim structures **502***a*, **502***b* configured in accordance with embodiments of the present technology, and FIG. **5**B is a perspective view of an individual shim structure **502***a*. Referring to FIGS. **5**A and **5**B together, the shim structures **502***a*, **502***b* can be inserted between the imaging arm **108** and the support arm **120** at the first and second sides **142**, **144** of the first interface **126**, respectively. The shim structures **502***a*, **502***b* can each include a first panel **504**, second panel **506**, and third panel **508** that are connected to each other to form a U-shaped structure. The shim structures **502***a*, **502***b* can each be positioned so that the first panel **504** fills the first gap **202**, the second panel **506** fills the second gap **204**, and the third panel **508** fills the third gap **206**. The first and third panels **504**, **508** can engage the upper and lower surfaces of the rails **138** to secure the

shim structures **502***a*, **502***b* to the imaging arm **108**. The panels **504-508** can be integrally formed with each other as a single unitary component, or can be separate components that are coupled to each other via adhesives, bonding, fasteners, etc. In the illustrated embodiment, the panels **504-508** are connected in a fixed geometry and are not movable relative to each other. In other embodiments, however, some or all of the panels **504-508** can be movably coupled to each other, as described further below.

[0103] The panels **504-508** can each be flattened, elongate members having a geometry (e.g., size, shape) selected to conform to the shape of the gaps **202-206**, respectively. For example, the angle between a pair of connected panels (e.g., the first and second panels **504**, **506**; the second and third panels **506**, **508**) can each independently be greater than or equal to 10°, 20°, 30°, 40°, 45°, 50°, 60°, 70°, 80°, 90°, 100°, 110°, 120°, 130°, 140°, 150°, 160°, or 170°. The panels **504-508** can each have any suitable shape, such as rectangular, square, etc. The dimensions of the panels **504-508** can also be varied as desired. In the illustrated embodiment, for example, the panels **504-508** have the same length L_5 (e.g., within a range from 1 cm to 20 cm) and thickness T_5 (e.g., within a range from 1 mm to 15 mm), but different widths W_5, W_6, and W_7, respectively. For example, the width W_5 of the first panel **504** can be greater than or equal to the width W_7 of the third panel **508**, which can be greater than the width W_6 of the second panel **506**. For example, the width W_5 can be within a range from 0.3 cm to 5 cm, the width W_6 can be within a range from 0.1 cm to 3 cm, and the width W_7 can be within a range from 0.3 cm to 5 cm. In other embodiments, however, the panels **504-508** can have different dimensions, e.g., the width W_6 can be greater than or equal to the width W_5 and/or the width W_7, some or all of the panels **504-508** can have different lengths, etc. Additionally, although the panels **504-508** are each depicted as having a uniform thickness T_5, in other embodiments, some or all of the panels **504-508** can instead have a variable thickness (e.g., a tapered thickness similar to the shim structure **302***c* of FIG. **3**C).

[0104] FIGS. **5**C and **5**D are perspective views of a U-shaped shim structure **502***c* with slidable connections configured in accordance with embodiments of the present technology. The shim structure **502***c* includes a first panel **510**, second panel **512**, and third panel **514** connected to each other via a first adjustable connection **516** and a second adjustable connection **518**. The first and second panels **510**, **512** can be coupled along their lateral edges by the first adjustable connection **516**, and the second and third panels **512**, **514** can be coupled their lateral edges by the second adjustable connection **518**. In the illustrated embodiment, the panels **510-514** each have a rectangular or square flattened section connected to a tapered section. In other embodiments, some or all of the panels **510-514** can have a different shape, as discussed elsewhere herein. Optionally, the panels **510-514** can be identical or similar to the panels **504-508** of FIGS. **5**A and **5**B, respectively.

[0105] The first and second adjustable connections **516**, **518** can each include any suitable attachment mechanism (e.g., joint, hinge, pivot, etc.) that allows the corresponding panels to move (e.g., translate and/or rotate) independently relative to each other. For example, as shown in FIGS. **5**C and **5**D, the first and second adjustable connections **516**, **518** can both be slidable connections (e.g., slidable dovetail connections) that allow the panels **510-514** to translate relative to each other, e.g., along a lengthwise direction **520**. The first and second adjustable connections **516**, **518** can include any of the features described above with respect to the adjustable connection **412** of FIGS. **4**C and **4**D.

[0106] The first and second adjustable connections **516**, **518** can allow the panels **510-512** to be moved independently to provide an improved fit with the first interface **126**. For example, the panels **510-514** can be sequentially inserted into the gaps **202-206**, respectively, of the first interface **126** (FIG. **5**A). In some embodiments, the shim structure **502***c* is initially placed in a partially separated configuration, such as the configuration shown in FIG. **5**C with the first panel **510** and third panel **514** displaced vertically relative to the second panel **512**. The panels **510-514**

can then be sequentially inserted into the corresponding gaps **202-206** in any suitable order. For example, the second panel **512** can be inserted before the first and third panels **510**, **514**; and then the first panel **510** can be inserted before the third panel **514**, or vice-versa. As another example, the first panel **510** can be inserted first, followed by the second panel **512**, and then the third panel **514**. When the shim structure **502***c* is fully inserted, the panels **510-514** can be generally aligned with each other, e.g., as shown in the configuration of FIG. **5**D.

[0107] FIG. **6**A is a partially schematic cross-sectional view of the first interface **126** with a set of U-shaped shim structures **602***a*, **602***b* configured in accordance with embodiments of the present technology, and FIG. **6**B is a perspective view of an individual shim structure **602***a*. Referring to FIGS. **6**A and **6**B together, the shim structures **602***a*, **602***b* can be inserted between the imaging arm **108** and the support arm **120** at the first and second sides **142**, **144** of the first interface **126**, respectively. The shim structures **602***a*, **602***b* can each include a first panel **604**, second panel **606**, and third panel **608** that are connected to each other to form a U-shaped structure. The shim structures **602***a*, **602***b* can each be positioned so that the first panel **604** fills the first gap **202**, the second panel **606** fills the second gap **204**, and the third panel **608** extends along an outer surface of the imaging arm **108** near the rail **138**. In some embodiments, the first and second panels **604**, **606** can inhibit movement of the imaging arm **108** relative to the support arm **120**, while the third panel **608** can engage the outer surface of the rail **138** to secure the shim structures **602***a*, **602***b* in place.

[0108] The panels **604-608** can be integrally formed with each other as a single unitary component, or can be separate components that are coupled to each other via adhesives, bonding, fasteners, etc. In some embodiments, the panels **604-608** are connected in a fixed geometry and are not movable relative to each other. In other embodiments, some or all of the panels **604-608** can be movably coupled to each other via adjustable connections, as previously described with reference to FIGS. **5**C and **5**D.

[0109] The panels **604-608** can each be flattened, elongate members having a geometry (e.g., size, shape) selected to conform to the shape of the gaps **202**, **204** and the outer surface of the imaging arm **108**. For example, the angle between any pair of connected panels (e.g., the first and second panels **604**, **606**; the first and third panels **604**, **608**) can each independently be greater than or equal to 10°, 20°, 30°, 40°, 45°, 50°, 60°, 70°, 80°, 90°, 100°, 110°, 120°, 130°, 140°, 150°, 160°, or 170°. The panels **604-608** can each have any suitable shape, such as rectangular, square, etc. The dimensions of the panels **604-608** can also be varied as desired. In the illustrated embodiment, for example, the panels **604-608** have the same length L.sub.8 (e.g., within a range from 1 cm to 20 cm) and thickness T.sub.5 (e.g., within a range from 1 mm to 15 mm), but different widths W.sub.8, W.sub.9, and W.sub.10, respectively. The width W.sub.8 of the first panel **604** can be greater than the width W.sub.9 of the second panel **606** and/or the width W.sub.10 of the third panel **608**. The width W.sub.9 of the second panel **606** can be equal to or greater than the width W.sub.10 of the third panel **608**. In some embodiments, the width W.sub.8 is within a range from 0.3 cm to 5 cm, the width W.sub.9 is within a range from 0.1 cm to 3 cm, and the width W.sub.10 is within a range from 0.1 cm to 3 cm. In other embodiments, however the panels **604-608** can have different dimensions, e.g., the width W.sub.8 can be less than or equal to the width W.sub.9 and/or the width W.sub.10, some or all of the panels **604-608** can have different lengths, etc. Additionally, although the panels **604-608** are each depicted as having a uniform thickness T.sub.8, in other embodiments, some or all of the panels **604-608** can instead have a variable thickness (e.g., a tapered thickness similar to the shim structure **302***c* of FIG. **3**C).

[0110] FIG. **7**A is a partially schematic cross-sectional view of the first interface **126** with a shim structure **702***a* and FIG. **7**B is a perspective view of the shim structure **702***a*, in accordance with embodiments of the present technology. Referring to FIGS. **7**A and **7**B together, the shim structure **702***a* includes a first arm region **704** and a second arm region **706** connected to each other by a bridge region **708** to form a flattened, horseshoe-shape or U-shaped structure. The first arm region **704** can be a flattened, elongate member (e.g., a panel, block, wedge) including a first end portion

712 coupled to one side of the bridge region **708**, and a second end portion **714** spaced apart from the bridge region **708**. Similarly, the second arm region **706** can be a flattened, elongate member (e.g., a panel, block, wedge) including a first end portion **716** coupled to the other side of the bridge region **708**, and a second end portion **718** spaced apart from the bridge region **708**. As best seen in FIG. **7**A, the first and second arm regions **704**, **706** can fit into the first gaps **202** at the first and second sides **142**, **144** of the first interface **126**, respectively to stabilize the imaging arm **108** and support arm **120**. The first and second arm regions **704**, **706** can be generally similar to the shim structures **302**a, **302**b of FIG. **3**A, except that the first and second arm regions **704**, **706** are connected to each other by the bridge region **708**, rather than being separate, discrete structures.

[0111] The bridge region **708** can be a flattened, elongate member (e.g., panel, block, strip, connector, etc.) that extends laterally from the first side **142** of the first interface **126** to the second side **144** of the first interface **126** to join the first and second arm regions **704**, **706** to each other. The regions **704**-**708** can be integrally formed with each other as a single unitary component, or can be separate components that are coupled to each other via adhesives, bonding, fasteners, etc. The regions **704**-**708** can be connected to each other in a fixed geometry, or can be movably coupled to each other via adjustable (e.g., slidable) connections as discussed elsewhere herein.

[0112] In some embodiments, the first and second arm regions **704**, **706** inhibit movement of the imaging arm **108** relative to the support arm **120**, while the bridge region **708** secures the first and second arm regions **704**, **706** in place, e.g., by applying an inward force on the first and second arm regions **704**, **706** during rotation of the imaging arm **108**. The bridge region **708** can also be beneficial for ensuring that the first and second arm regions **704**, **706** are positioned at substantially the same insertion depth into the first gaps **202** at both sides **142**, **144** of the first interface **126**. Optionally, the shim structure **702**a can also include a handle connected to the bridge region **708** (not shown) to facilitate insertion and/or removal of the shim structure **702**a from the first interface **126**.

[0113] The geometry (e.g., size, shape) of the first and second arm regions **704**, **706** can be selected to conform to the shape of the first gaps **202**. Additionally, the geometry and configuration of the regions **704**-**708** can define a recess or cavity **710** in the shim structure **702**a that accommodates the outer surface of the distal portion **122** of the support arm **120** and/or the imaging arm **108**. In the illustrated embodiment, the first and second arm regions **704**, **706** and the bridge region **708** each have a rectangular shape. In other embodiments, however, any of the regions **704**-**708** can have a different shape (e.g., square, triangular, etc.). The dimensions of the regions **704**-**708** can also be varied as desired. In the illustrated embodiment, for example, the first and second arm regions **704**, **706** have the same length L.sub.11 (e.g., within a range from 1 cm to 20 cm), width W.sub.11 (e.g., within a range from 0.3 cm to 5 cm), and thickness T.sub.11 (e.g., within a range from 1 mm to 15 mm). Alternatively, the first and second arm regions **704**, **706** can have different lengths, widths, and/or thicknesses.

[0114] The bridge region **708** can have a length L**12** that is less than the length Lu of the first and second arm regions **704**, **706**. For example, the length L**12** can be less than or equal to 10 cm, or within a range from 5 cm to 0.3 cm. The bridge region **708** can have a width W.sub.12 that is greater than or equal to the width W.sub.11 of the first and second arm regions **704**, **706**. For example, the width W.sub.12 can be within a range from 5 cm to 10 cm, or from 3 cm to 10 cm. In other embodiments, however, the width W.sub.12 can be less than the width W.sub.11 of the first and second arm regions **704**, **706**. The bridge region **708** can have the same thickness T.sub.11 as the first and second arm regions **704**, **706** or can have a different (e.g., larger or smaller) thickness.

[0115] FIG. **7**C is a perspective view of a shim structure **702**b configured in accordance with embodiments of the present technology. The shim structure **702**b can be identical or generally similar to the shim structure **702**a of FIGS. **7**A and **7**B, except that the first arm region **704** and second arm region **706** each have a tapered and/or wedge-like shape. As shown in FIG. **7**C, the first and second arm regions **704**, **706** each have a first thickness T.sub.13 at their first end portions **712**,

716, and a second thickness T.sub.14 at their second end portions **714**, **718**. The first thickness T.sub.13 can be greater than the second thickness T.sub.14. For example, the first thickness T.sub.13 can be at least 3 mm, 4 mm, 5 mm, 6 mm, 7 mm, 8 mm, 9 mm, 10 mm, or 15 mm, or within a range from 4 mm to 8 mm. The second thickness T.sub.14 can be less than 5 mm, 4 mm, 3 mm, 2 mm, 1 mm, 0.5 mm, or 0.1 mm, or within a range from 4 mm to 0.1 mm. Optionally, the first and second arm regions **704**, **706** can each be tapered to have a triangular cross-sectional shape (e.g., similar to the shim structure **302**c of FIG. **3**C), with the angle at the respective second end portion **714**, **718** being less than or equal to 80°, 70°, 60°, 50°, 45°, 40°, 35°, 30°, 25°, 20°, 15°, 10°, or 5°.

[0116] FIG. **7**D is a perspective view of the shim structure **702**b positioned at the first interface **126** in accordance with embodiments of the present technology. As shown in FIG. **7**D, the shim structure **702**b is positioned at one end of the first interface **126**, with the first and second arm regions **704**, **706** inserted into the spaces between the imaging arm **108** and the distal portion **122** of the support arm **120**, and the bridge region **708** extending laterally across the imaging arm **108**. The presence of the bridge region **708** can help the user visually confirm whether the first and second arm regions **704**, **706** are positioned at the substantially the same insertion depth within the first interface **126**, which can be beneficial for improving mechanical stability during manual rotation. Optionally, another shim structure identical or similar to the shim structure **702**b can be positioned at the other end of the first interface **126** (not shown in FIG. **7**D).

[0117] FIGS. **7**E-**7**H illustrate additional shim structures **702**c-**702**f configured in accordance with embodiments of the present technology. The shim structures **702**c-**702**f can be generally similar to the shim structures **702**a, **702**b of FIGS. **7**A-**7**D. Accordingly, the discussion of the shim structures **702**c-**702**f will be limited to those features that differ from the embodiments of FIGS. **7**A-**7**D. Additionally, any of the features of the shim structures **702**c-**702**f can be combined with the embodiment of FIGS. **7**A-**7**D and/or with each other.

[0118] FIG. **7**E is a perspective view of a shim structure **702**c including a set of ridges **720** configured in accordance with embodiments of the present technology. The ridges **720** can be elongated, raised structures located at or near the inner edges of the first and second arm regions **704**, **706**. In the illustrated embodiment, each ridge **720** extends only partially along the length of the respective first or second arm region **704**, **706**, and terminates before the location where the arm region connects to the bridge region **708**. In other embodiments, however, each ridge **720** can extend along the entire length of the respective first or second arm region **704**, **706**. When the shim structure **702**c is inserted into the first interface **126**, the ridges **720** can extend above the surfaces of the first and second arm regions **704**, **706** to further secure the shim structure **702**c in place.

[0119] FIG. **7**F is a perspective view of a shim structure **702**d including a plurality of protrusions **722** configured in accordance with embodiments of the present technology. As shown in FIG. **7**F, the protrusions **722** are located along the inner surfaces of the first and second arm regions **704**, **706** and extend inward into the recess **710**. When the shim structure **702**d is positioned at the first interface **126**, the protrusions **722** can engage the distal portion **122** of the support arm **120** to secure the shim structure **702**d in place. The shim structure **702**d can include any suitable number of protrusions **722**, such as one, two, three, four, five, ten, fifteen, twenty, or more protrusions **722**. Although the protrusions **722** are depicted as being rounded, semi-circular bumps, in other embodiments the protrusions **722** can have a different shape, such as square, rectangular, triangular, etc. Optionally, the protrusions **722** can be angled toward the bridge region **708** to further lock the shim structure **702**d into place. The dimensions and spacing of the protrusions **722** can also be varied as desired. For example, the protrusions **722** can each have a width and/or height within a range from 1 mm to 10 mm, and can be spaced apart from each other by a distance within a range from 1 mm to 10 mm.

[0120] FIG. **7**G is a perspective view of a shim structure **702**e including a plurality of square or rectangular notches **724**. As shown in FIG. **7**G, the notches **724** are located along the inner surfaces

of the first and second arm regions **704**, **706**. The notches **724** can create a tooth-like texture along the inner surfaces of the first and second arm regions **704**, **706** to improve engagement between the shim structure **702***e* and the support arm **120**. The shim structure **702***e* can include any suitable number of notches **724**, such as one, two, three, four, five, ten, fifteen, twenty, or more notches **724**. The dimensions and spacing of the notches **724** can be varied as desired, e.g., the notches **724** can each have a width and/or depth within a range from 1 mm to 10 mm, and can be spaced from each other by a distance within a range from 1 mm to 10 mm.

[0121] FIG. **7**H is a perspective view of a shim structure **702***f* including a plurality of triangular notches **726**. The notches **726** can be oriented so that the base of each triangular notch **726** is connected to the recess **710** and the apex of each triangular notch **726** points away from the recess **710**. The spacing, size, and function of the notches **726** can otherwise be generally similar to the square or rectangular notches **724** of FIG. **7**G.

[0122] In some embodiments, when the shim structures described herein are placed in the first interface **126** between the imaging arm **108** and support arm **120**, the shim structure can reduce or prevent the imaging arm **108** from sliding relative to the support arm **120**, thus inhibiting orbital rotation of the imaging arm **108**. Alternatively, the shim structures described herein can be configured to permit orbital rotation of the imaging arm **108**, which may improve convenience and case of use.

[0123] FIG. **8**A is a partially schematic cross-sectional view of the first interface with a set of shim structures **802***a*, **802***b* with rollers **804**, and FIG. **8**B is a perspective view of an individual shim structure **802***a*, in accordance with embodiments of the present technology. The shim structures **802***a*, **802***b* can each include a panel **806**, e.g., similar to the shim structures **302***a*, **302***b* of FIGS. **3**A and **3**B. One or more rollers **804** (e.g., wheels, ball bearings, etc.) can be embedded in or otherwise coupled to the panel **806**. The rollers **804** can protrude out of the upper and/or lower surfaces of the panel **806**. Accordingly, when the shim structure **802***a*, **802***b* are inserted in the first interface **126**, the rollers **804** can contact the surfaces of the imaging arm **108** and/or support arm **120** to allow these components to slide relative to each other. In the illustrated embodiment, for example, the rollers **804** contact the lower surfaces of the rails **138** of the imaging arm **108** and the upper surfaces of the grooves **146** formed in the distal portion **122** of the support arm **120**. Thus, the imaging arm **108** can still be rotated in an orbital rotation direction while being stabilized by the shim structures **802***a*, **802***b* for propeller rotation.

[0124] In some embodiments, the shim structures described herein are configured to be permanently or temporarily attached to the imaging apparatus **104**, even when not in use. For example, the shim structure can be coupled to a portion of the imaging apparatus **104** (e.g., to the imaging arm **108**) via a mounting mechanism. The mounting mechanism can allow the shim structure to be moved between an engaged configuration, in which the shim structure is stabilizing the imaging apparatus **104** for manual rotation as described elsewhere herein, and a disengaged configuration, in which the shim structure remains attached to the imaging apparatus **104** by the mounting mechanism but is not stabilizing the imaging apparatus **104**. In the disengaged configuration, the components of the imaging apparatus **104** (e.g., the imaging arm **108** and support arm **120**) can move freely relative to each other without being obstructed by the shim structure. This approach allows the operator to quickly and easily switch between stabilized and non-stabilized operation of the imaging apparatus **104**, while reducing the likelihood of the shim structure being lost when not in use.

[0125] FIGS. **9**A-**9**F illustrate a shim structure **902** with a mounting mechanism **904** configured in accordance with embodiments of the present technology. Referring first to FIG. **9**A, which is a partially schematic top view of the shim structure **902**, the shim structure **902** is a flattened, U-shaped structure that is generally similar to the shim structures **702***a* and **702***b* of FIGS. 7A-7D. For example, the shim structure **902** can include a first arm region **906**, a second arm region **908**, and a bridge region **910** connecting the first and second arm regions **906**, **908**. The shim structure **902** can

optionally include a handle **912** coupled to the bridge region **910** to allow an operator to engage and disengage the shim structure **902** from the first interface **126** of the imaging apparatus **104**, as described further below.

[0126] In some embodiments, the mounting mechanism **904** is also a flattened, U-shaped structure including a respective first arm region **914**, second arm region **916**, and bridge region **918**. The first arm region **914** of the mounting mechanism **904** can be coupled to the first arm region **906** of the shim structure **902** via a first hinge **920**, and the second arm region **916** of the mounting mechanism **904** can be coupled to the second arm region **908** of the shim structure **902** via a second hinge **922**. The bridge region **918** can be a bar or similar structure that engages a portion of the imaging apparatus **104** to prevent the shim structure **902** from being removed from the imaging arm **108**.

[0127] FIGS. **9**B and **9**C are partially schematic side views of the shim structure **902** and mounting mechanism **904** in a straightened state (FIG. **9**B) and a bent state (FIG. **9**C). As shown in FIG. **9**B, in the straightened state, the longitudinal axis of the shim structure **902** can be generally aligned with (e.g., parallel to) the longitudinal axis of the mounting mechanism **904**. As shown in FIG. **9**C, in the bent state, the shim structure **902** can pivot relative to the mounting mechanism **904** around the first and second hinges **920, 922**, such that the longitudinal axis of the shim structure **902** is offset from (e.g., perpendicular to) the longitudinal axis of the mounting mechanism **904**.

[0128] FIGS. **9**D-**9**F are partially schematic side views of the shim structure **902** and mounting mechanism **904** during use, in accordance with embodiments of the present technology. Referring first to FIG. **9**D, the mounting mechanism **904** can be positioned at the first interface **126** between the imaging arm **108** and the distal portion **122** of the support arm **120**. In some embodiments, the bridge region **918** of the mounting mechanism **904** is inserted into the grooves **146** (FIG. **1**C) between the distal portion **122** of the support arm **120** and the rails **138** (FIG. **1**C) of the imaging arm **108**, in an orientation extending laterally across the track **140** (FIG. **1**C) of the imaging arm **108**. Accordingly, the distal portion **122** of the support arm **120** located within the track **140** can obstruct the mounting mechanism **904**, and thus, the shim structure **902**, from being removed from the first interface **126**. In such embodiments, the shim structure **902** can be coupled to the mounting mechanism **904** after the mounting mechanism **904** has been inserted into the first interface **126**.

[0129] When stabilization is not needed, the shim structure **902** can be placed in a disengaged configuration as shown in FIG. **9**D. In the disengaged configuration, the shim structure **902** is positioned out of and away from the first interface **126**. To prevent the shim structure **902** from inadvertently sliding into the first interface **126** (e.g., due to gravity or if bumped by an operator), the shim structure **902** can be rotated into the bent state. In some embodiments, the bridge region **918** of the mounting mechanism **904** is sufficiently low-profile such that the imaging arm **108** can move relative to the support arm **120** (e.g., along an orbital rotation direction) when the shim structure **902** is in the disengaged configuration.

[0130] Referring next to FIG. **9**E, when stabilization is desired, the operator can rotate the shim structure **902** into the straightened state using the handle **912**. Subsequently, the operator can place the shim structure **902** into an engaged configuration as shown in FIG. **9**F by advancing the shim structure **902** into the first interface **126** using the handle **912**. In the engaged configuration, the first and second arm regions **906, 908** of the shim structure **902** can be positioned in the gaps between the support arm **120** and imaging arm **108** to inhibit unwanted movements, as described elsewhere herein. Once the imaging procedure is complete, the shim structure **902** can be retracted out of the first interface **126** and folded back into the disengaged configuration of FIG. **9**D.

[0131] FIG. **10**A is a partially schematic cross-sectional view of the first interface **126** of imaging apparatus **104** with a shim structure **1002** and mounting mechanism **1004**, and FIG. **10**B is a front view of the shim structure **1002** and mounting mechanism **1004**, in accordance with embodiments of the present technology. As best seen in FIG. **10**B, the shim structure **1002** is a flattened, U-shaped structure that is generally similar to the shim structures **702***a* and **702***b* of FIGS. **7**A-**7**D. For

example, the shim structure **1002** can include a first arm region **1006**, a second arm region **1008**, and a bridge region **1010** connecting the first and second arm regions **1006**, **1008**.

[0132] Referring to FIGS. **10**A and **10**B together, the mounting mechanism **1004** includes a first knob **1012** attached to a first gear **1014** that is coupled to the first arm region **1006** of the shim structure **1002**, and a second knob **1016** attached to a second gear **1018** that is coupled to the second arm region **1008** of the shim structure **1002**. The first and second knobs **1012**, **1016** can each be rotated by an operator to turn the first and second gears **1014**, **1018**, which in turn translate the shim structure **1002** between a disengaged configuration and an engaged configuration, as described further below. Optionally, the first and second gears **1014**, **1018** can be coupled to each other via a connector **1020** (e.g., a crossbar), such that the first and second arm regions **1006**, **1008** are concurrently translated even when only one of the knobs **1012**, **1016** is rotated. This configuration can be advantageous for ensuring that the first and second arm regions **1006**, **1008** are advanced into the gaps at the first and second sides **142**, **144**, respectively, of the first interface **126** (FIG. **10**A) by the same or similar distances.

[0133] FIGS. **10**C and **10**D are partially schematic side views of the shim structure **1002** and mounting mechanism **1004** during use, in accordance with embodiments of the present technology. Referring first to FIG. **10**C, the mounting mechanism **904** can be positioned at the first interface **126** between the imaging arm **108** and the distal portion **122** of the support arm **120**. In some embodiments, the connector **1020** of the mounting mechanism **1004** is inserted into the grooves **146** (FIG. **1**C) between the distal portion **122** of the support arm **120** and the rails **138** (FIG. **1**C) of the imaging arm **108**, in an orientation extending laterally across the track **140** (FIG. **1**C) of the imaging arm **108**. Alternatively, the connector **1020** can be positioned outside and laterally across the distal portion **122** of the support arm **120**.

[0134] When stabilization is not needed, the shim structure **1002** can be placed in a disengaged configuration as shown in FIG. **10**C. In the disengaged configuration, the shim structure **1002** is positioned out of and away from the first interface **126**. When stabilization is desired, the operator can rotate the first and/or second knobs **1012**, **1016** of the mounting mechanism **1004** to place the shim structure **1002** into an engaged configuration as shown in FIG. **10**D. The rotation of the first and/or second knobs **1012**, **1016** can turn the first and/or second gears **1014**, **1018** to advance the shim structure **1002** forward relative to the mounting mechanism **1004** and into the first interface **126**. In the engaged configuration, the first and second arm regions **1006**, **1008** of the shim structure **1002** can be positioned in the gaps between the support arm **120** and imaging arm **108** to inhibit unwanted movements, as described elsewhere herein. Once the imaging procedure is complete, the first and/or second knobs **1012**, **1016** can be rotated in the reverse direction to turn the first and/or second gears **1014**, **1018** backward to retract the shim structure **1002** relative to the mounting mechanism **1004** and out of the first interface **126**.

[0135] FIG. **11** is a graph illustrating motion of an IMU on a C-arm detector with and without shim stabilization. The motion data was generated by an IMU with an accelerometer while the C-arm was manually rotated through a continuous 180° propeller rotation. The x-axis represents the rotational position of the C-arm as measured by the IMU. The y-axis represents the degree of off-plane motion of the IMU during the rotation (e.g., unwanted motion). In the illustrated embodiment, there is ideally little or no off-plane motion (e.g., line **1102**), indicating that the detector is moving within a single rotational plane. In the absence of shim structures (line **1104**), the IMU motion data includes significant oscillations and sharp changes in slope, corresponding to sudden weight shifts and reverberations that occur due to mechanical laxity and weight imbalances between the C-arm detector and source. These movements can be variable and inconsistent between rotations, which can make it difficult or impossible to compensate for such movements using the calibration processes described further below. However, when shim structures are used (line **1106**), the IMU motion data exhibits a smooth trajectory with a generally constant slope (in FIG. **11**, the C-arm was stabilized with two shim structures similar to the shim structure **702**b of

FIGS. **7**C and **7**D). The shim structures can also allow the C-arm to move in a generally consistent trajectory over multiple rotations, which can make it feasible to compensate for the off-plane motion using the calibration processes described further below. As shown in FIG. **11**, the shim structures can help with reducing off-plane motion, but may not eliminate it completely. Any residual off-plane motion can be compensated for via a geometric calibration process, as described in greater detail below.

[0136] FIG. **12** illustrates an example of unwanted movements that may occur at the second interface **128** during a manual rotation of the imaging arm **108**. In some instances, the location(s) at which force is applied may affect the stability of the imaging arm **108** during manual rotation. Specifically, certain locations may be more likely to produce unwanted and/or non-uniform movements when pushed and/or pulled during manual rotation. For example, when performing a manual propeller rotation, it may be mechanically advantageous to apply force to the first and second end portions **114**, **116** of the imaging arm **108**, since these locations are located farther from the center of rotation (also known as the "pivot point"), and thus require less force to initiate and/or maintain rotation. However, in situations where the second interface **128** is mechanically unstable (e.g., due to spaces, gaps, or other mechanical laxity between the base **118** and support arm **120**), applying force to the first and second end portions **114**, **116** of the imaging arm **108** may produce greater torque on the second interface **128**, which can cause the support arm **120** and imaging arm **108** to shift relative to the base **118** (e.g., along a translational direction **1202**) or otherwise exhibit unwanted and/or non-uniform motions.

[0137] In some embodiments, the amount of torque on the second interface **128** can be reduced by applying the rotational force to the proximal portion **124** of the support arm **120** at or near the second interface **128**, rather than to the imaging arm **108**. However, because this location is closer to the pivot point, the amount of force to perform a manual propeller rotation may be significantly increased. Additionally, the proximal portion **124** of the support arm **120** may lack handles or grips to facilitate manual rotation, or the handle at that location may be too small to offer sufficient leverage. Accordingly, to reduce the amount of force for performing a manual propeller rotation at or near the second interface **128**, the present technology can provide a temporary or permanent lever structure that attaches to the proximal portion **124** of the support arm **120** near the second interface **128** to provide greater mechanical advantage for rotation.

[0138] FIGS. **13**A-**14**E illustrate representative examples of lever structures that can be used to facilitate manual rotation of an imaging apparatus, in accordance with embodiments of the present technology. Although the lever structures of FIGS. **13**A-**14**E are described and illustrated with reference to components of the imaging apparatus **104** of FIG. **1**A, it will be appreciated that the lever structures can also be used with other imaging apparatuses and systems. Additionally, any of the features of the lever structures of FIGS. **13**A-**14**E can be combined with each other.

[0139] FIG. **13**A is a partially schematic view of the imaging apparatus **104** with a lever structure **1302***a* and FIG. **13**B is a closeup, cross-sectional view of the support arm **120** with the lever structure **1302***a*, in accordance with embodiments of the present technology. The lever structure **1302***a* is configured to temporarily or permanently attach to the support arm **120** to assist a user in applying a rotational force to the proximal portion **124** of the support arm **120** during a propeller rotation. As best seen in FIG. **13**B, the lever structure **1302***a* includes a handle **1304** coupled to a clamp **1306**. The clamp **1306** can include a pair of clamp members **1308** connected to a crossbar **1310** in a fixed geometry. The lever structure **1302***a* can have a fork-like configuration in which one end of the handle **1304** is coupled to the central portion of the crossbar **1310**, and the clamp members **1308** are coupled to the end portions of the crossbar **1310** and extend longitudinally away from the crossbar **1310**.

[0140] The handle **1304** can be an elongate rod or shaft configured to be held by one or both of the user's hands. The handle **1304** can be sufficiently long to provide leverage for rotating the support arm **120** and imaging arm **108**. In some embodiments, for example, the handle **1304** has a length

within a range from 10 cm to 70 cm. Optionally, the handle **1304** can include texturing, coatings, an ergonomic shape, and/or other suitable features to improve grip.

[0141] The clamp members **1308** can be elongate prongs, arms, etc., configured to secure the lever structure **1302***a* to the proximal portion **124** of the support arm **120** at or near the second interface **128**. The clamp members **1308** can be configured to fit tightly around the support arm **120** so that the lever structure **1302***a* does not become dislodged when the user applies force to the handle **1304**. For example, the spacing between the clamp members **1308** can be within a range from 5 cm to 20 cm. The spacing can be identical or similar to the cross-sectional dimension of the proximal portion **124** of the support arm **120** to provide a tight fit around the support arm **120**. In the illustrated embodiment, the clamp members **1308** are affixed to the crossbar **1310** at an angle, such that the spacing between the clamp members **1308** increases with distance from the crossbar **1310**. This configuration can allow the clamp members **1308** to fit snugly around the support arm **120** near the pivot point during rotation. Alternatively, the clamp members **1308** can be substantially parallel to each other, such that the spacing between the clamp members **1308** is constant. Each clamp member **1308** can have a length within a range from 10 cm to 30 cm, and a thickness and/or diameter within a range from 1 cm to 5 cm. The clamp members **1308** can have any suitable cross-sectional shape (e.g., square, rectangular, circular).

[0142] FIG. **13**C is a cross-sectional view of the support arm **120** with an adjustable lever structure **1302***b* configured in accordance with embodiments of the present technology. The lever structure **1302***b* can be generally similar to the lever structure **1302***a* of FIGS. **13**A and **13**B, except that the lever structure **1302***b* includes an adjustable clamp member **1314** that can be moved along the crossbar **1310**, and a fixed clamp member **1316** that remains stationary. The adjustable clamp member **1314** can be moved relative to the fixed clamp member **1316** to alter the clamp spacing, which can allow the clamp **1312** to accommodate different support arm geometrics. In the illustrated embodiment, for example, the adjustable clamp member **1314** is coupled to a trigger **1318** for repositioning the adjustable clamp member **1314**. When the trigger **1318** is squeezed, the adjustable clamp member **1314** can slide along the crossbar **1310** toward and/or away from the fixed clamp member **1316**. When the trigger **1318** is released, the adjustable clamp member **1314** can be locked in place at its current position along the crossbar **1310**. Optionally, the clamp **1312** can include teeth, detents, and/or other ratchet-like features so the adjustable clamp member **1314** is movable to a plurality of different predetermined locations along the crossbar **1310**.

[0143] FIG. **13**D is a cross-sectional view of the support arm **120** with another adjustable lever structure **1302***c* configured in accordance with embodiments of the present technology. The lever structure **1302***c* includes a handle **1304** coupled to a clamp **1320** (e.g., a C-clamp, G-clamp, U-clamp). The clamp **1320** can include a frame **1322** (e.g., a curved, square, or rectangular bracket) having an adjustable pad **1324** at one end, and a fixed pad **1326** at the other end. The handle **1304** can be connected to the central portion of the frame **1322** between the two ends. The adjustable pad **1324** can be coupled to a screw **1328** that is rotatable to alter the position of the adjustable pad **1324**. Accordingly, the user can turn the screw **1328** to change the spacing between the adjustable pad **1324** and fixed pad **1326** to accommodate different support arm geometries.

[0144] FIG. **14**A is a partially schematic view of the imaging apparatus **104** with a lever structure **1402***a* and FIG. **14**B is a front view of the lever structure **1402***a*, in accordance with embodiments of the present technology. Referring first to FIG. **14**A, in some embodiments, the imaging apparatus **104** already includes a handle **1404** at or near the proximal portion **124** of the support arm **120** near the second interface **128**. However, the handle **1404** may be too small to provide sufficient mechanical advantage for manually rotating the support arm **120** and imaging arm **108**. Accordingly, the lever structure **1402***a* can be temporarily or permanently coupled to the handle **1404** to provide a longer lever arm and/or otherwise increase the mechanical advantage.

[0145] Referring next to FIG. **14**B, the lever structure **1402***a* can include a first elongate member **1406** (e.g., a rod, shaft, or tube) having a pair of hooks **1408**. The hooks **1408** can engage the

handle **1404** (FIG. **14**A) to secure the lever structure **1402***a* to the support arm **120**. The lever structure **1402***a* can also include a second elongate member **1410** (e.g., a rod, shaft, or tube) connected to the first elongate member **1406** between the hooks **1408**. The second elongate member **1410** can be attached to the first elongate member **1406** at a 90° angle or any other suitable angle. During use, the user can grip the first elongate member **1406** and/or second elongate member **1410** to apply a rotational force to the support arm **120** for propeller rotation. In other embodiments, the second elongate member **1410** can be omitted, such that the user applies force using the first elongate member **1406** only.

[0146] FIG. **14**C is a front view of a lever structure **1402***b* configured in accordance with embodiments of the present technology. The lever structure **1402***b* is identical to the lever structure **1402***a* of FIGS. **12**A and **12**B, except that the lever structure **1402***b* includes a third hook **1412** on the second elongate member **1410**. The third hook **1412** can further secure the lever structure **1402***b* to the handle **1404** on the support arm **120** (FIG. **14**A). It will be appreciated that lever structure **1402***a*, **1402***b* of FIGS. **14**A-**14**C can include any suitable number of hooks (e.g., one, two, three, four, five, or more hooks), and the hooks can be at any suitable location on the first elongate member **1406** and/or the second elongate member **1410**.

[0147] FIGS. **14**D and **14**E are partially schematic cross-section views of an adjustable lever structure **1402***c* coupled to the handle **1404** of the imaging apparatus **104**, in accordance with embodiments of the present technology. Although the lever structure **1402***c* is depicted as having two hooks **1408** (e.g., similar to the lever structure **1402***a* of FIGS. **14**A and **14**B), in other embodiments, the lever structure **1402***c* can instead have three hooks (e.g., similar to the lever structure **1402***b* of FIG. **14**C). Referring first to FIG. **14**D, the first elongate member **1406** of the lever structure **1402***c* can include a first section **1414** and a second section **1416** connected to each other by an adjustable connection **1418**. The adjustable connection **1418** can allow the first and second sections **1414**, **1416** to be moved (e.g., translated) relative to each other along the longitudinal axis of the first elongate member **1406**. The adjustable connection **1418** can be any suitable joint or mechanism that permits movement of the first section **1414** relative to the second section **1416**, such as a slidable mechanism (e.g., a slidable bolt), a screw mechanism (e.g., a threaded bolt), a spring-loaded mechanism, or a combination thereof.

[0148] The first and second sections **1414**, **1416** can each include at least one hook **1408**, such that the distance between the hooks **1408** can be increased or decreased by changing the separation between the first and second sections **1414**, **1416**. For example, the hooks **1408** can be positioned closer together in a retracted configuration (FIG. **14**D) when initially positioning the lever structure **1402***c* on the handle **1404**, and can then be pushed outwards into an extended configuration (FIG. **14**E) to contact and grip the handle **1404**. This approach can make it easier to connect the lever structure **1402***c* to the handle **1404**, while also providing a tighter fit to prevent the lever structure **1402***c* from inadvertently becoming dislodged when force is applied.

[0149] In some embodiments, the systems, methods, and devices disclosed herein reduce or eliminate unwanted movements during manual rotation, as measured by some or all of the following metrics: (1) imaging arm motion (e.g., as measured by an IMU or other motion sensor), (2) amount and type of unwanted motion in the projection images generated by the detector, (3) image quality of the 3D reconstruction generated from the projection images, and/or (4) physical distance between the imaging arm and the support arm. Each of these metrics is described in detail below.

[0150] First, as previously discussed with respect to FIG. **11**, in the absence of any stabilization, the detector exhibits sudden shifts, oscillations, and/or other unwanted movements. When stabilized with shim structures and/or by rotation from the support arm, these undesirable movements can be significantly reduced to produce a relatively smooth and unidirectional rotation of the detector.

[0151] Second, in the absence of stabilization, undesirable motions (e.g., caused by weight shifts and/or flexing of the imaging arm) can be seen in the projection images as a sudden jump in all the

structures in the field of view in the same direction simultaneously. This can indicate that the center of rotation of the detector was rapidly shifting back and forth, rather than maintaining a single center of rotation, since all the structures moved together in the same direction (whereas during a rotation, there are often structures moving in opposite directions based on depth). Further, during and/or after the initial shift, the structures may reverse direction briefly as the imaging arm moves backwards with the oscillations. When the imaging arm is stabilized using shim structures and/or the other techniques described herein, the sudden jumps in the projection image and/or reversed movements can be reduced or eliminated entirely.

[0152] Third, it may be difficult or impossible to generate coherent 3D reconstructions without using the stabilization techniques described herein. For example, the unwanted motions of the detector can change the center of rotation, thus causing some or all of the structures in the 3D reconstruction to be misaligned. In some instances, when imaging a marker bead in a phantom, the misalignment can cause the bead to appear as star-like shape in the 3D reconstruction, rather than a coherent spherical shape. Similarly, when imaging a cylindrical phantom with circular markers, the misalignment can cause the circles to appear as discontinuous half-circles in the 3D reconstruction, rather than a single continuous circle. This misalignment can be reduced or eliminated by using shim structures and/or rotating from the support arm to improve the stability of the imaging arm and/or detector during image acquisition, e.g., in combination with the calibration processes described below.

[0153] Fourth, in the absence of shim stabilization, the components of the imaging arm (e.g., the rails) and the support arm (e.g., the distal portion of the support arm) can be displaced by a distance within a range from 1 mm to 5 mm as measured at various angular rotation points. When shim structures are used, it may be nearly impossible for the imaging arm rails to move relative to the support arm since the shim structures can reduce or prevent the laxity between these components, thus producing a smoother, more uniform motion during image acquisition.

B. Sensors and Methods for Pose Estimation

[0154] Referring again to FIG. **1**A, as previously discussed, during an mrCBCT procedure, the imaging arm **108** can be rotated to a plurality of different angles while the detector **112** obtains 2D images of the patient's anatomy. In some embodiments, to generate a 3D reconstruction from the 2D images, the pose of the imaging arm **108** needs to be determined for each image with a high degree of accuracy. However, as described above, a manually-operated imaging apparatus such as a mobile C-arm apparatus may lack the capability to track the pose of the imaging arm **108** with sufficient accuracy for CBCT purposes.

[0155] Accordingly, the system **100** can include at least one sensor **154** for tracking the pose of the imaging arm **108** during a manual rotation. The sensor **154** can be positioned at any suitable location on the imaging apparatus **104**. In the illustrated embodiment, for example, the sensor **154** is positioned on the detector **112**. Alternatively or in combination, the sensor **154** can be positioned at a different location, such as on the radiation source **110**, on the imaging arm **108** (e.g., at or near the first end portion **114**, at or near the second end portion **116**), on the support arm **120** (e.g., at or near the distal portion **122**, at or near the proximal portion **124**), and so on. Additionally, although FIG. **1**A illustrates a single sensor **154**, in other embodiments, the system **100** can include multiple sensors **154** (e.g., two, three, four, five, or more sensors **154**) distributed at various locations on the imaging apparatus **104**. For example, the system **100** can include a first sensor **154** on the detector **112**, a second sensor **154** on the radiation source **110**, etc. The sensors **154** can be removably coupled or permanently affixed to the imaging apparatus **104**.

[0156] In some embodiments, because the spatial configuration of the various components of the imaging apparatus **104** are known, the pose of the imaging arm **108** can be correlated to the pose of other components of the imaging apparatus **104**. For example, in embodiments where the detector **112** is in a fixed position and orientation with respect to the imaging arm **108**, the pose of the detector **112** can be calculated from the pose of the imaging arm **108**, and vice-versa. Accordingly,

any embodiment described herein as using the pose of the imaging arm **108** can alternatively or additionally be adapted to use the pose of the detector **112** (or any other suitable component of the imaging apparatus **104**).

[0157] The sensor **154** can be any sensor type suitable for tracking the pose (e.g., position and/or orientation) of a movable component. For example, the sensor **154** can be configured to track the rotational angle of the imaging arm **108** during a manual propeller rotation. Examples of sensors **154** suitable for use with the imaging apparatus **104** include, but are not limited to, motion sensors (e.g., IMUs, accelerometers, gyroscopes, magnetometers), light and/or radiation sensors (e.g., photodiodes), image sensors (e.g., video cameras), EM sensors (e.g., EM trackers or navigation systems), shape sensors (e.g., shape sensing fibers or cables), or suitable combinations thereof. In embodiments where the system **100** includes multiple sensors **154**, the sensors **154** can be the same or different sensor types. For example, the system **100** can include two motion sensors, a motion sensor and a photodiode, a motion sensor and a shape sensor, etc.

[0158] In some embodiments, the sensor **154** includes at least one motion sensor, such as a 9-axis IMU having an accelerometer, gyroscope, and/or magnetometer. The motion sensor can be configured to generate motion data (e.g., position and/or orientation data over time) as the imaging arm **108** is manually rotated. The motion sensor can be attached to any portion of the imaging apparatus **104** that undergoes rotation, such as the detector **112**, radiation source **110**, imaging arm **108**, support arm **120**, or a combination thereof. In some embodiments, two or more motion sensors are used, with each motion sensor being attached to a different portion of the imaging apparatus **104** (e.g., a first motion sensor can be attached to the detector **112** and a second motion sensor can be attached to the radiation source **110**).

[0159] FIG. **15** is a partially schematic view of a motion sensor **1502** coupled to the imaging apparatus **104** via an attachment device **1504** configured in accordance with embodiments of the present technology. The motion sensor **1502** is coupled to the attachment device **1504**, which in turn is coupled to the detector **112** of the imaging apparatus **104**. In the embodiment of FIG. **15**, the attachment device **1504** is configured to attach to the lateral surface of the detector **112**. In other embodiments, however, the attachment device **1504** can be configured to attach to a different portion of the detector **112**, such as the upper surface, lower surface, etc. Optionally the detector **112** and/or the attachment device **1504** can include alignment markings (e.g., lines, arrows, or other indicators) to guide the user in placing the attachment device **1504** (and thus, the motion sensor **1502**) at a predetermined position and/orientation on the detector **112**.

[0160] In the illustrated embodiment, the attachment device **1504** is configured as a clip or bracket that attaches to the edge of the detector **112** at or near the lower surface. The clip can include a small, vertically-oriented peg having a short lip or overhanging protrusion that grips onto the lower edge of the detector **112**. Optionally, the clip can be spring-loaded, can include a rotatable screw, and/or can be otherwise configured to lock into place once positioned at the desired location on the detector **112**. In other embodiments, however, the attachment device **1504** can be configured differently. For example, the attachment device **1504** can instead be configured as a container for holding the motion sensor **1502**, such as a small rectangular box that can be placed flat against a flat portion of the detector **112**. The container can include loops, handles, apertures, etc., allowing the container to be secured to the detector **112** using straps (e.g., straps made of velcro or other adhesive material) and/or other fasteners. Optionally, the attachment device **1504** can be omitted altogether, the motion sensor **1502** can instead be coupled directly to the detector **112** via adhesives, fasteners, magnets, straps, etc.

[0161] The motion sensor **1502** can generate motion data indicative of the pose of the imaging arm **108**. For example, as the imaging arm **108** moves (e.g., during a manual propeller rotation), the motion sensor **1502** can output motion data representing the position and/or orientation (e.g., rotational angle) of the imaging arm **108** over time. In some embodiments, the motion sensor **1502** generates motion data independently of the image acquisition performed by the detector **112**.

Accordingly, in order to determine the pose of the imaging arm **108** for each image obtained by the detector **112**, the motion data from the motion sensor **1502** can be temporally synchronized or otherwise associated with the images from the detector **112**.

[0162] The synchronization can be performed in many different ways. In the illustrated embodiment, for example, the motion sensor **1502** is coupled to a controller **1506** (e.g., an Arduino microcontroller), which in turn is coupled to an image output device **1508**. The image output device **1508** can receive the images generated by the detector **112** (e.g., in video format or any other suitable format). As shown in FIG. **15**, the images produced by the detector **112** can be transmitted to the base **118**, and the base **118** can be coupled to the image output device **1508**. In other embodiments, the detector **112** can be coupled directly to the image output device **1508**. The connections between the motion sensor **1502**, controller **1506**, image output device **1508**, detector **112**, and base **118** can be wired or wireless connections.

[0163] The controller **1506** can collect the motion data from the motion sensor **1502** in real time and temporally synchronize each image acquired by the image output device **1508** with the motion data from the motion sensor **1502**. For example, the controller **1506** can time stamp the motion data received from the motion sensor **1502**. The controller **1508** can then compare the time stamps for the motion data to the time stamps on the image data, and can associate each image with motion data that was acquired at the same time point or over a similar time period. Thus, each image recorded from the image output device **1508** can be associated with a corresponding angle (or a very small range of angles) from the motion sensor **1502**.

[0164] FIG. **16** is a partially schematic view of a motion sensor **1602** and radiation sensor **1604** attached to the imaging apparatus **104** in accordance with embodiments of the present technology. The motion sensor **1602** (e.g., IMU) and radiation sensor **1604** can be coupled to an attachment device **1606**. The attachment device **1606** can be generally similar to the attachment device **1504** of FIG. **15**, except that the attachment device **1606** is configured to support both the motion sensor **1602** and the radiation sensor **1604**. For example, the attachment device **1606** can be a clip with a vertically-oriented peg that can be temporarily coupled to the detector **112**. The attachment device **1606** can be mounted on the detector **112** such that the motion sensor **1602** is located along the lateral surface of the detector **112**, while the radiation sensor **1604** protrudes at least partially into the path of the radiation beam output by the detector **112**.

[0165] The radiation sensor **1604** can be any device capable of detecting exposure to radiation (e.g., x-rays), such as a photodiode. For example, the photodiode can include a scintillator made of silicon-based materials and/or other suitable materials, and can be provided with or without a signal amplifier. Accordingly, the radiation sensor **1604** can accurately measure the time of image acquisition based on exposure radiation passing through the radiation sensor **1604** toward the detector **112**.

[0166] The motion sensor **1602** and radiation sensor **1604** can each be coupled to a controller **1608** (e.g., an Arduino microcontroller) via wired or wireless connections. When the radiation sensor **1604** detects radiation, it can send a signal to the controller **1608** to generate a time stamp indicating that an image was acquired. Similarly, the controller **1608** can also determine time stamps for the motion data produced by the motion sensor **1602**. Accordingly, the image acquisition timing can be linked to the timing of the rotational measurements from the motion sensor **1602**, thus allowing each image generated by the detector **112** to be temporally synchronized to the corresponding rotational angle of the imaging arm **108**.

[0167] FIG. **17**A is a top view of an attachment device **1702***a*, FIG. **17**B is a side view of the attachment device **1702***a*, and FIG. **17**C is a partially schematic illustration of the attachment device **1702***a* coupled to the imaging apparatus **104**, in accordance with embodiments of the present technology. Referring first to FIGS. **17**A and **17**B together, the attachment device **1702***a* is configured to support a motion sensor **1704** (e.g., an IMU) and a radiation sensor **1706** (e.g., a photodiode). The attachment device **1702***a* can include a frame **1708** and one or more clips **1710**

located along the periphery of the frame **1708**. Although the frame **1708** is depicted as having a circular shape, in other embodiments, the frame **1708** can have a different shape, such as an oval, square, rectangular, or other suitable shape. The frame **1708** can include a central aperture **1712** to allow radiation to pass through. The frame **1708** can also be used to support a fiducial marker grid for a calibration procedure, as described in detail further below.

[0168] The clips **1710** can be configured to couple the attachment device **1702***a* to the detector **112** in a temporary or permanent manner. In some embodiments, the clips **1710** are small, vertically-oriented pegs located at the edge of the frame **1708**, each having a short lip or overhanging protrusion to grip onto the edge of the detector **112**. As best seen in FIG. **17**C, the clips **1710** can secure the attachment device **1702***a* to the lower surface of the detector **112**, with the frame **1708** located partially or entirely out of the radiation path of the detector **112** to avoid attenuating or otherwise interfering with the radiation beam. Optionally, the detector **112**, frame **1708**, and/or clips **1710** can include alignment markers to guide the user in placing the attachment device **1702***a* at the appropriate position and/or orientation on the detector **112**.

[0169] In some embodiments, the attachment device **1702***a* includes one or more sites along the frame **1708** and/or clips **1710** for attaching the motion sensor **1704** and/or radiation sensor **1706**. For example, the motion sensor **1704** and radiation sensor **1706** can both be coupled to one of the clips **1710**, similar to the configuration of the attachment device **1606** of FIG. **16**. The motion sensor **1704** can be located along an edge of the attachment device **1702***a* away from the path of the radiation beam, while the radiation sensor **1706** can protrude at least partially under the frame **1708** and into path of the radiation beam. In other embodiments, however, the motion sensor **1704** and/or radiation sensor **1706** can be at different locations on the attachment device **1702***a*. The motion sensor **1704** and/or radiation sensor **1706** can each be removably coupled to the attachment device **1702***a* or permanently affixed to the attachment device **1702***a*. The motion sensor **1704** and radiation sensor **1706** can be coupled to other components (e.g., controller, image output device) for temporally synchronizing the output of the motion sensor **1704** with the images produced by the detector **112**, as discussed above with respect to FIGS. **15** and **16**. Optionally, the radiation sensor **1706** can be omitted, such that the attachment device **1702***a* is used to support the motion sensor **1704** only.

[0170] FIG. **17**D is a side view of an attachment device **1702***b* configured in accordance with embodiments of the present technology. The attachment device **1702***b* can be generally similar to the attachment device **1702***a* of FIGS. **15**A-**15**C, except that the attachment device **1702***b* includes a spring-loaded clip **1714** in place of one or more of the clips **1710**. The clip **1714** can include a spring-loaded protrusion **1716** that can be retracted when positioning the attachment device **1702***b* on the detector **112**. After the attachment device **1702***b* is positioned at the desired location, the spring-loaded protrusion **1716** can lock into place around the edge of the detector **112** to secure the frame **1708** to the detector **112**. The clip **1714** can include a release mechanism (not shown) to retract the spring-loaded protrusion **1716** when removing and/or mounting the frame **1708**. The attachment device **1702***b* can optionally be configured to support a motion sensor and/or radiation sensor (not shown in FIG. **17**D), as discussed above with reference to FIGS. **17**A and **17**B. The attachment device **1702***b* can also be used to support a fiducial marker grid for a calibration procedure, as described in detail further below.

[0171] FIG. **17**E is a side view of an attachment device **1702***c* configured in accordance with embodiments of the present technology. The attachment device **1702***c* can be generally similar to the attachment device **1702***a* of FIGS. **15**A-**15**C, except that the attachment device **1702***c* includes a screw **1718** in place of one or more of the clips **1710**. The screw **1718** can be in a retracted position when placing the attachment device **1702***c* on the detector **112**. After the attachment device **1702***c* is positioned at the desired location, the screw **1718** can be rotated to advance the screw **1718** toward the detector **112**. The screw **1718** can be advanced until it engages the edge of the detector **112**, thus securing the frame **1708** to the detector **112**. To release the attachment device

1702*c*, the screw **1718** can be rotated in the opposite direction to retract the screw **1718** away from the detector **112**. The attachment device **1702***c* can optionally be configured to support a motion sensor and/or radiation sensor (not shown in FIG. **17**E), as discussed above with reference to FIGS. **17**A and **17**B. The attachment device **1702***c* can also be used to support a fiducial marker grid for a calibration procedure, as described in detail further below.

[0172] Referring again to FIG. **1**A, the present technology also provides other techniques that may be used to estimate the pose of the imaging arm **108**, alternatively or in addition to the motion sensor-based techniques described herein. For example, in some embodiments, the pose of the imaging arm **108** can determined using one or more imaging devices (e.g., video cameras) positioned around the imaging apparatus **104**. In such embodiments, the system **100** can include one or more fiducial markers placed at known locations, such as on the patient **102**, operating table **152**, and/or the components of the imaging apparatus **104** (e.g., detector **112**, radiation source **110**, imaging arm **108**, and/or support arm **120**). The imaging devices can track the markers as the imaging arm **108** is rotated to determine the pose of the imaging arm **108**.

[0173] In another example, the system **100** can include a 3D scanner coupled to the imaging arm **108**. The 3D scanner can be configured to scan a reference object (e.g., a block) attached to a fixed location relative to the imaging arm **108**, such as to the operating table **152** and/or the patient's body. The reference object can have a known geometry, such that the pose of the imaging arm **108** can be determined from the pose of the reference object within the scans.

[0174] As another example, the pose of the imaging arm **108** can be determined using shape sensors (e.g., shape-sensing fibers or cables). For example, one portion of a shape-sensing cable can be attached to the operating table **152**, and another portion to the detector **112**. Alternatively or in combination, one or more shape-sensing cables can be attached to other locations, such as to the patient **102**, radiation source **110**, imaging arm **108**, support arm **120**, or suitable combinations thereof. When the imaging arm **108** is rotated, the change in shape of the shape-sensing cable can be measured and used to calculate the rotational angle of the imaging arm **108**.

[0175] In a further example, a shape sensor can be carried by a tool within the patient's body, such as a shape-sensing endoscope. For example, the tool can output shape data that allows the 3D pose of the tool to be accurately determined before image acquisition. The pose of the internal shape sensor in each projection image can be used to estimate the pose of the imaging arm **108** when the image was acquired. For example, the actual pose of the tool can be output as a virtual rendering or representation of the 3D shape of the tool inside the patient's body. The pose of the internal shape sensor within the images can be identified (e.g., using known computer vision and/or image processing techniques), and registered to the virtual representation of the actual pose. The registration can be used to determine the pose of the imaging arm with respect to the tool and/or the patient's body for each acquired image.

[0176] In yet another example, an EM sensing system can be used to determine the pose of the imaging arm **108** during rotation. For example, one or more EM sensors or trackers can be positioned at various locations, such as on the patient **102**, operating table **152**, detector **112**, radiation source **110**, imaging arm **108**, support arm **120**, or suitable combinations thereof. The position and/orientation of each EM sensor can be tracked and used to estimate the angle of the imaging arm **108**. Optionally, an EM sensor can also be carried by a tool within the patient's body, such as an endoscope, biopsy needle, ablation probe, etc. The internal EM sensor can be used in combination with one or more externally-located EM sensors to perform pose estimation.

[0177] In some embodiments, the pose of the imaging arm is estimated using a fiducial marker board placed near the patient's body, as an alternative to or in combination with the other pose estimation techniques described herein. Conventional fiducial marker boards for intraprocedural image-based pose estimation (e.g., for tomosynthesis) are typically flat structures with one or more layers of markers. Conventional fiducial marker boards are generally unsuitable for imaging techniques involving a large angular range of rotation such as CBCT because the markers in the

board may not be visible at certain angles due to the limited vertical height of the board. For example, the markers in a conventional fiducial marker board may be obscured or disappear entirely from the field of view when imaged from a lateral angle (e.g., at or near 180°). In contrast, the fiducial marker boards of the present technology can have a 3D shape in which at least some of the markers lie in different planes or are otherwise sufficiently vertically separated so most or all of the markers remain visible over a wide range of imaging angles. This allows for estimation of the imaging arm pose over a wide range of imaging angles. Additionally, conventional fiducial marker boards are generally unsuitable for determining the geometric calibration parameters of the imaging apparatus (e.g., piercing point, pitch, roll, etc.). The fiducial marker boards disclosed herein can be combined with a fiducial marker phantom in order to perform geometric calibration, which can improve the accuracy of the CBCT reconstruction as described in greater detail below.

[0178] FIG. **18**A is a side view of a fiducial marker board **1800** for determining the pose of an imaging arm, and FIG. **18**B is a top view of the fiducial marker board **1800**, in accordance with embodiments of the present technology. The fiducial marker board **1800** can be positioned adjacent or near a patient's body to provide a reference for estimating a pose of an imaging arm. The fiducial marker board **1800** includes a substrate **1802** (e.g., a radiolucent material) containing a plurality of fiducial markers **1804** (e.g., beads, bearings, flattened disks, etc., made of a radiodense or radiopaque material). The markers **1804** can be arranged in a known geometry (e.g., a grid, pattern, or other spatial configuration) such that when the fiducial marker board **1800** is imaged by an imaging apparatus, the pose of the imaging apparatus (e.g., the angle of the imaging arm) relative to the fiducial marker board **1800** can be determined based on the locations of the markers **1804** in the acquired images, in accordance with techniques known to those of skill in the art.

[0179] As best seen in FIG. **18**A, the substrate **1802** can have a non-planar shape (e.g., a curved, semicircular, semioval, and/or U shape) such that at least some of the markers **1804** are in different planes. In the illustrated embodiment, for example, the substrate **1802** includes a base region **1806** and a pair of curved sidewalls **1808** extending upward from the base region **1806** by a height H.sub.1. For example, the height H.sub.1 can be at least 1 cm, 2 cm, 5 cm, 10 cm, 15 cm, 20 cm, or 30 cm. In some embodiments, the height H.sub.1 is greater than or equal to the anterior-posterior height of a patient's torso. The height H.sub.1 can be sufficiently large such that most or all of the markers **1804** remain visible even when the fiducial marker board **1800** is imaged from a lateral angle (e.g., at or near 180° relative to the surface of the table). Accordingly, the fiducial marker board **1800** can be used to estimate the pose of the imaging arm over a wider range of angles compared to flat fiducial marker boards in which most or all of the markers lie within a single plane. Optionally, the sidewalls **1808** can be movably coupled to the base region **1806** (e.g., via a sliding or pivoting connection) so that the height H.sub.1 can be adjusted, e.g., to accommodate different body sizes and/or imaging setups.

[0180] During a medical procedure, the fiducial marker board **1800** can be placed on a operating table with the base region **1806** resting on a surface of the table, and the sidewalls **1808** extending upward away from the surface. A portion of the patient's body (e.g., the patient's torso) can be positioned on the fiducial marker board **1800** in the cavity formed by the base region **1806** and sidewalls **1808**. A plurality of 2D projection images can be acquired while the imaging arm of the imaging apparatus is rotated to a plurality of different angles relative to the patient's body and the fiducial marker board **1800**. The 2D projection images can then be analyzed to identify the locations of the markers **1804** in each image, e.g., using computer vision algorithms or other suitable algorithms. Optionally, in embodiments where the markers **1804** are made of a metallic material, the images can be processed to remove any imaging artifacts caused by the presence of the metallic material. The identified marker locations can be used to estimate the rotational angle of the imaging arm for each image, using techniques known to those of skill in the art.

[0181] FIGS. **18**C-**18**G illustrate additional examples of fiducial marker boards **1810-1840** suitable for use with the present technology. The features of the fiducial marker boards **1810-1840** can be

generally similar to the features of the fiducial marker board **1800** of FIGS. **18**A and **18**B. Accordingly, the discussion of the fiducial marker boards **1810-1840** of FIGS. **18**C-**18**G will be limited to those features that differ from the embodiments of FIGS. **18**A and **18**B. Any of the features of the fiducial marker boards **1810-1840** can be combined with each other and/or with the features of the fiducial marker board **1800** of FIGS. **18**A and **18**B.

[0182] FIG. **18**C is a side view of another fiducial marker board **1810** configured in accordance with embodiments of the present technology. As shown in FIG. **18**C, the markers **1804** in the fiducial marker board **1810** are located only in a portion of the substrate **1802**, rather than being distributed throughout the entirety of the substrate **1802**. For example, the markers **1804** can be localized to one lateral side or half of the substrate **1802**, such that only one of the sidewalls **1808** includes markers **1804**. This configuration can be used, for example, in situations where only a single side or section of the patient's body is to be imaged (e.g., during a bronchoscopic procedure performed within a single lung). In such situations, the fiducial marker board **1810** can be positioned so that the markers **1804** are near the side or section of the patient's body to be imaged.

[0183] FIG. **18**D is a side view of yet another fiducial marker board **1820** configured in accordance with embodiments of the present technology. The fiducial marker board **1820** includes a single sidewall **1808**, rather than two sidewalls **1808**. In such embodiments, the base region **1806** can be extended to provide support for the sidewall **1808**, such that the fiducial marker board **1820** is J-shaped. Although the base region **1806** is depicted without any markers **1804**, in other embodiments the base region **1806** can also include markers **1804**. The fiducial marker board **1820** can be used when imaging a single side or section of the patient's body. In such situations, the fiducial marker board **1820** can be positioned so that the single sidewall **1808** is near the side or section of the patient's body to be imaged.

[0184] FIG. **18**E is a side view of a fiducial marker board **1830** configured in accordance with embodiments of the present technology. The fiducial marker board **1830** includes a flattened base region **1832** and a pair of straight sidewalls **1834**. The sidewalls **1834** can be connected to the base region **1832** at any suitable angle, such as an angle greater than or equal to 90°, 110°, 120°, 130°, 140°, or 150°. The height H_2 of the sidewalls **1834** can be sufficiently large so that that most or all of the markers **1804** remain visible even when the fiducial marker board **1830** is imaged from a lateral angle, and can be identical or similar to the height H_1 of the fiducial marker board **1800** of FIGS. **18**A and **18**B. Optionally, the sidewalls **1834** can be movably coupled to the base region **1832** so the height H_2 can be adjusted, if desired.

[0185] Although the fiducial marker board **1830** is illustrated as including markers **1804** throughout the entirety of the substrate **1802**, in other embodiments the fiducial marker board **1830** can include markers **1804** in only a portion of the substrate **1802** (e.g., similar to the fiducial marker board **1820** of FIG. **18**C). Additionally, although the fiducial marker board **1830** is shown as having two sidewalls **1834**, in other embodiments the fiducial marker board **1830** can include a single sidewall **1834** (e.g., similar to the fiducial marker board **1830** of FIG. **18**D).

[0186] FIGS. **18**F and **18**G are side and top views, respectively, of a fiducial marker board **1840** together with a fiducial marker phantom **1842**, in accordance with embodiments of the present technology. The fiducial marker board **1840** can be similar to the fiducial marker board **1830** of FIG. **18**E, except that the fiducial marker board **1840** includes a single sidewall **1834** connected to the base region **1832**. The phantom **1842** can be temporarily coupled to the fiducial marker board **1840** via one or more fasteners **1844** (e.g., pegs, screws, magnets, etc.). The phantom **1842** can include a respective substrate **1846** (e.g., a radiolucent material) containing a plurality of fiducial markers **1848** (e.g., beads, bearings, flattened disks, etc., made of a radiodense or radiopaque material). The markers **1848** can be arranged in a configuration suitable for performing geometric calibration, as described further below with respect to FIGS. **22**A-**22**D.

[0187] As best seen in FIG. **18**G, the phantom **1842** can be positioned over a portion of the base region **1832** that does not include any markers **1804**. In such embodiments, when the fiducial

marker board **1840** and phantom **1842** are imaged together (e.g., during a geometric calibration procedure), the markers **1804** of the fiducial marker board **1840** do not overlap the markers **1848** of the phantom **1842** in the acquired images, and thus can be identified and distinguished from each other. The use of the phantom **1842** together with the fiducial marker board **1840** for performing geometric calibration and image acquisition is described in further detail below with respect to FIG. **25**A.

C. Methods for Imaging

[0188] FIGS. **19-25** illustrate various methods for imaging an anatomic region of a patient with an imaging apparatus such as a mobile C-arm apparatus. Specifically, FIG. **19** provides a general overview of the imaging process, FIGS. **20-22**D illustrate methods and devices for calibrating the imaging apparatus, FIGS. **23**A and **23**B illustrate methods for image acquisition and reconstruction, FIG. **24** illustrates a method for preparing the imaging apparatus for imaging, and FIG. **25**A illustrates a method for calibration and imaging using a fiducial marker board. The methods disclosed herein can be performed using any embodiment of the systems and devices described herein, such as the system **100** of FIG. **1**A. Any of the methods disclosed herein can be performed by an operator (e.g., a physician, nurse, technician, or other healthcare professional), by a computing device (e.g., the computing device **130** of FIG. **1**A), or suitable combinations thereof. For example, some processes in a method can be performed manually by an operator, while other processes in the method can be performed automatically or semi-automatically by one or more processors of a computing device.

[0189] FIG. **19** is a flow diagram illustrating a method **1900** for operating an imaging apparatus for mrCBCT imaging, in accordance with embodiments of the present technology. The method **1900** can be performed with a manually-operated imaging apparatus (e.g., a mobile C-arm apparatus) or any other suitable imaging system or device. The method **1900** begins at block **1902** with stabilizing the imaging apparatus. As discussed above, mrCBCT imaging can involve stabilizing the imaging apparatus to reduce or prevent undesirable and/or inconsistent movements (e.g., oscillations, jerks, shifts, flexing, etc.) during manual rotation. For example, the imaging arm can be stabilized using one or more shim structures, such as any of the embodiments described herein with respect to FIGS. **1**A and **3**A-**10**D. Alternatively or in combination, the imaging arm can be rotated by applying force to the support arm (e.g., to the proximal portion of the support arm at or near the center of rotation), rather than by applying force to the imaging arm. As previously described, the force can be applied via one or more lever structures coupled to the support arm, such as any of the embodiments described herein with respect to FIGS. **13**A-**14**E. In other embodiments, however, the imaging arm can be manually rotated without any shim structures and/or without applying force to the support arm.

[0190] Alternatively or in combination, the stabilization process of block **1902** can include other processes. For example, block **1902** can also include adjusting the orbital tilt of the imaging arm to improve weight balance and/or ensure the detector surface remains close to tangential to the path of the detector during rotation. Optionally, a motion sensor (e.g., IMU) can be used to provide feedback about the stability of the imaging arm and/or the effectiveness of specific stabilization steps. For example, the feedback can include information characterizing the quality of the stabilization (e.g., are there residual oscillations, should the shims be repositioned), whether the movement trajectory of the imaging arm was satisfactory (e.g., was there significant tilt during the rotation, which may be improved by adjusting the orbital tilt of the C-arm and/or adjusting the shim configuration), and so on. The motion sensor can be attached to any suitable location on the imaging apparatus, such as the detector, radiation source, imaging arm, and/or support arm.

[0191] At block **1904**, the method **1900** continues with calibrating the imaging apparatus. Calibration can be used to compensate for the variations in the imaging environment and/or mechanical properties of the imaging apparatus that may affect image reconstruction. In some embodiments, calibration includes determining one or more calibration parameters (e.g., distortion

correction parameters, geometric calibration parameters) that are used in the subsequent image acquisition and/or image reconstruction processes to adjust for the particular characteristics of the imaging apparatus. Additional details of methods and devices suitable for use in the calibration process of block **1904** are described below with reference to FIGS. **20-22**D.

[0192] FIG. **20** is a flow diagram illustrating a method **2000** for calibrating an imaging apparatus, in accordance with embodiments of the present technology. The method **2000** can be performed as part of the calibration process of block **1904** of the method **1900** of FIG. **19**. As shown in FIG. **20**, the calibration process can be subdivided into two parts: distortion correction (blocks **2002** and **2004**) and geometric calibration (blocks **2006** and **2008**).

[0193] Distortion correction can be performed in embodiments where one or more components of the imaging apparatus (e.g., the detector) are prone to image distortion that may reduce the accuracy of the subsequent 3D reconstruction. For example, mobile C-arm apparatuses commonly use an image intensifier as the detector, and the images generated by the image intensifier can exhibit pincushion and/or barrel distortion, among others. The distortion can also change depending on the pose (e.g., angle) of the image intensifier. Accordingly, the method **2000** can include performing a distortion correction process to identify the amount of image distortion at various poses of the imaging arm, and determine correction parameters that can be applied to the images to reduce or eliminate distortion. In other embodiments, the distortion correction process can be omitted, e.g., if using a flat panel detector rather than an image intensifier.

[0194] At block **2002**, the method **2000** can include obtaining one or more first images of a first set of fiducial markers ("first fiducial markers"). The first fiducial markers can be radiodense or radiopaque beads, bearings, etc., that are arranged in a known 2D or 3D geometry, such as a grid, array, pattern, shape, etc. The first fiducial markers can be coupled to the detector in a fixed spatial configuration relative to the detector. The first images can be 2D projection images of the first fiducial markers acquired by the detector as the imaging arm is manually rotated through a plurality of different poses (e.g., rotation angles). Each first image can be associated with a corresponding pose of the imaging arm using any of the devices and techniques described elsewhere herein, such as the embodiments of FIGS. **15-18**E.

[0195] At block **2004**, the method **2000** continues with determining a set of distortion correction parameters based on the first images. The first images can be transmitted to a computing device (e.g., the computing device **130** of FIG. **1**A), and the computing device can analyze the first images to detect the locations of the first fiducial markers in the first images (e.g., using image processing and/or computer vision techniques known to those of skill in the art). The computing device can then determine the distortion correction parameters by comparing the locations of the first fiducial markers in the first images to the known, true locations of the first fiducial markers on the grid, array, etc. The distortion correction parameters can represent a set of transformations (e.g., rigid and/or non-rigid transformations such as rotation, translation, deformation, etc.) that would realign the first fiducial markers in the distorted images to their true locations. The distortion correction parameters can be determined through an optimization process according to techniques known to those of skill in the art. This process can be performed for each image to determine the appropriate distortion correction parameters for different poses (e.g., angles) of the imaging arm. The determined distortion correction parameters can then be applied to each image individually to remove distortion artifacts due to the properties of the detector and/or the pose of the detector, as discussed in greater detail below.

[0196] FIG. **21**A is a front view of a fiducial marker grid **2102***a* configured in accordance with embodiments of the present technology. The grid **2102***a* can be used to determine distortion correction parameters for an imaging apparatus, e.g., as described above with respect to blocks **2002-2004** of FIG. **20**. The grid **2102***a* includes a substrate **2104** containing a plurality of fiducial markers **2106**. The substrate **2104** can be made of a radiolucent material, such as acrylonitrile butadiene styrene (ABS), among others. In the illustrated embodiment, the substrate **2104** has a

circular shape. In other embodiments, the substrate **2104** can have a different shape, such as square, rectangular, oval, etc. The substrate **2104** can be sized to fit partially or entirely over the surface of a typical detector. For example, the substrate **2104** can have a diameter and/or width within a range from 9 inches to 12 inches.

[0197] The markers **2106** can be beads, bearings, flattened disks, etc., made of a radiodense or radiopaque material, such as steel or other metallic material. As shown in FIG. **21**A, the markers can be arranged in a regular (e.g., square) grid. In some embodiments, the markers **2106** have a size (e.g., diameter and/or width) within a range from 0.5 mm to 3 mm, and are spaced from each other by a distance of 1 cm. In other embodiments, the size and/or arrangement of the markers **2106** can be varied as desired. The grid **2102***a* can include any suitable number of discrete markers, such as at least 10, 25, 50, 100, 200, 300, 400, 500, 600, 700, 800, 900, 1000, or more markers.

[0198] During use, the grid **2102***a* can be placed adjacent or near the surface of the detector so that some or all of the markers **2106** are within the field of view of the detector. The grid **2102***a* can be temporarily coupled to the detector via clips, brackets, clamps, suction cups, velcro straps, rubber bands, magnets, or any other suitable attachment mechanism. Optionally, the grid **2102***a* and/or detector can include one or more alignment markers so the grid **2102***a* can be coupled to the detector at a consistent position and/or orientation.

[0199] In some embodiments, the grid **2102***a* is coupled to an attachment device that is connected to the detector. For example, the attachment device **1702***a* of FIGS. **17**A-**17**E can be used to mount the grid **2102***a* to the detector. In such embodiments, the attachment device **1702***a* can be coupled to the detector, and the grid **2102***a* can be inserted into or otherwise coupled to the frame **1708** of the attachment device **1702***a*. After the distortion correction process has been completed, the grid **2102***a* can be removed from the frame **1708** while leaving the attachment device **1702***a* in place, or the attachment device **1702***a* and grid **2102***a* can be removed together.

[0200] Optionally, the grid **2102***a* can include functional components such as a motion sensor (e.g., an IMU) and/or a radiation sensor (e.g., a photodiode). The motion sensor and radiation detector can be used to track the pose of the imaging arm and temporally synchronize the pose data to the acquired images, as discussed above. These components can be embedded in or otherwise coupled to the peripheral portion of the grid **2102***a* to avoid obscuring the field of view of the detector. In other embodiments, however, the grid **2102***a* can be provided without the motion sensor and/or the radiation sensor.

[0201] FIGS. **21**B-**21**D are front views of additional fiducial marker grids **2102***b*-**2102***d* configured in accordance with embodiments of the present technology. The grids **2102***b*-**2102***d* can be generally similar to the grid **2102***a* of FIG. **21**A. Accordingly, the discussion of the grids **2102***b*-**2102***d* will be limited to those features that differ from the grid **2102***a* of FIG. **21**A.

[0202] Referring first to FIG. **21**B, the markers **2106** in the grid **2102***b* are arranged so that the central portion **2108** has a different pattern than the peripheral portion **2110**. This approach can facilitate automated identification of the central portion **2108** of the grid **2102***b*, which can simplify the optimization process for calculating the distortion correction parameters. In FIG. **21**B, for example, the five markers **2106** at the central portion **2108** are connected with radiodense or radiopaque lines to form a cross shape. In FIG. **21**C, the central marker **2106** at the central portion **2108** of the grid **2102***c* is spaced apart from the other markers **2106** by a known radial distance, so that the central portion **2108** has a lower marker density than the peripheral portion **2110**. In FIG. **21**D, the central portion **2108** of the grid **2102***d* includes additional markers **2106**, so that the central portion **2108** has a higher marker density than the peripheral portion **2110**. Alternatively or in combination, other types of patterns, shapes, geometries, etc., can be used to distinguish the central portion **2108** from the peripheral portion **2110**.

[0203] Referring again to FIG. **20**, the geometric calibration process of the method **2000** can include characterizing the geometry of the imaging apparatus during a manual rotation. In some embodiments, geometric calibration is required because of the mechanical instabilities of the

imaging apparatus, which can lead to shifting and/or other non-uniform motions during rotation as described above. For example, the manual rotation can cause the imaging arm to deviate from the ideal rotation path (e.g., a single plane, circular rotation path) for CBCT imaging purposes. Additionally, the components of the imaging apparatus may shift during manual rotation, e.g., the internal components of the detector may shift relative to the outer housing. Such internal movements may be difficult or impossible to detect using an externally-placed sensor (e.g., an IMU coupled to the detector housing), and thus may require an image-based calibration process. In some embodiments, the changes in geometry during rotation cause the projection images acquired by the imaging apparatus to be misaligned (e.g., the center of rotation shifts between images), which can detrimentally affect the quality and accuracy of the 3D reconstruction.

[0204] Accordingly, the method **2000** can include determining the geometry of the imaging apparatus at various rotational positions in order to determine deviations and/or other movements that may occur during subsequent rotations. Based on the determined geometry, the method **2000** can compute a set of geometric calibration parameters that can be used to adjust the projection images to compensate for the changes in geometry during rotation. For example, the geometric calibration parameters can represent a set of transformations that, when applied to the projection images, corrects any misalignment present in the images due to unwanted movements of the imaging apparatus.

[0205] At block **2006**, the method **2000** includes obtaining second images of a second set of fiducial markers ("second fiducial markers"). The second fiducial markers can be radiodense or radiopaque beads, bearings, etc., that are positioned within a phantom in a known 3D configuration. The second images can be 2D projection images acquired by the detector as the imaging arm is manually rotated to a plurality of different poses relative to the phantom. In some embodiments, the phantom is positioned at or near the isocenter of the imaging arm, and the imaging arm is manually rotated around the phantom (e.g., in a propeller rotation direction) to obtain the second images of the phantom from a plurality of different rotational angles. Each second image can be associated with a corresponding pose of the imaging arm using any of the devices and techniques described elsewhere herein, such as the embodiments of FIGS. **15-18**E. In embodiments where the pose is determined using a fiducial marker board (e.g., the fiducial marker boards **1800-1830** of FIGS. **18**A-**18**E), the phantom can be mounted on or otherwise coupled to the fiducial marker board in a known spatial configuration (e.g., using a stand, at a fixed location on the operating table, etc.).

[0206] At block **2008**, the method **2000** continues with determining a set of geometric calibration parameters based on the second images. The second images can be transmitted to a computing device (e.g., the computing device **130** of FIG. **1**A) for analysis. In some embodiments, the computing device first corrects any image distortion present in the second images using the distortion correction parameters determined in block **2004**. The computing device can then analyze the second images to detect the locations of the second fiducial markers in the second images (e.g., using image processing and/or computer vision techniques known to those of skill in the art). Subsequently, the computing device can use the imaged locations of the second fiducial markers and the known 3D configuration of the second fiducial markers in the phantom to determine the geometry of the imaging apparatus during rotation, such as the piercing point, skewness, pitch, roll, tilt, and/or source-to-detector distance, among others. For example, the piercing point can represent the center of rotation of the imaging arm and/or the center of the reference coordinate system in the image data. The geometry of the imaging apparatus can be determined using image-based geometric calibration algorithms known to those of skill in the art.

[0207] Subsequently, the geometric calibration parameters can be computed based on the determined geometry of the imaging apparatus. As discussed above, the geometric calibration parameters can represent a set of transformations (e.g., rigid and/or non-rigid transformations such as rotation, translation, deformation, etc.) for adjusting the projection images at each rotational

angle of the imaging apparatus to correct any misalignment present. For example, if the piercing point of the imaging apparatus shifts for a particular angle of the imaging arm, the projection image acquired at that angle can be shifted in the opposite direction to realign the piercing point. The determined geometric calibration parameters can be applied to each image individually to realign the images in preparation for image reconstruction, as discussed in greater detail below.

[0208] FIG. **22**A is a perspective view of a fiducial marker phantom **2202***a* configured in accordance with embodiments of the present technology. The phantom **2202***a* can be used to perform geometric calibration for an imaging apparatus, e.g., as described above with respect to blocks **2006-2008** of FIG. **20**. The phantom **2202***a* includes a substrate **2204** containing a plurality of fiducial markers **2206**. The substrate **2204** can be made of a radiolucent material (e.g., ABS) and can be manufactured using 3D printing or other suitable techniques. In the illustrated embodiment, the substrate **2204** has an elongated, cylindrical shape. The substrate **2204** can have a length within a range from 7 cm to 25 cm, and a diameter within a range from 7 cm to 25 cm.

[0209] Optionally, the substrate **2204** can be hollow, with a sidewall thickness within a range from 0.5 cm to 5 cm. In other embodiments, however, the geometry (e.g., size, shape) of the substrate **2204** can be varied as desired, e.g., the substrate **2204** can be rectangular rather than cylindrical, the substrate **2204** can be solid rather than hollow, etc.

[0210] The markers **2206** can be beads, bearings, flattened disks, etc., made of a radiodense or radiopaque material, such as steel or other metallic material. The markers **2206** can be embedded in the phantom **2202***a* at known spatial locations. In the illustrated embodiment, for example, the markers **2206** are arranged in two parallel circles at the first end **2208** and second end **2210** of the substrate **2204**. This arrangement can allow the piercing point to be automatically identified in images of the phantom **2202***a* by connecting diametrically opposed markers **2206** and determining the intersection of the connections, in accordance with techniques known to those of skill in the art. In other embodiments, however, the markers **2206** can be arranged in a different geometry and/or can be positioned at different locations in the substrate **2204** (e.g., between the first and second ends **2208**, **2210**).

[0211] FIG. **22**B is a perspective view of another fiducial marker phantom **2202***b* configured in accordance with embodiments of the present technology. The phantom **2202***b* can be generally similar to the phantom **2202***a* of FIG. **22**A, except that the phantom **2202***b* includes a central marker **2212** representing the piercing point of the imaging apparatus. The central marker **2212** can be a bead, bearing, etc., made of a radiodense or radiopaque material, such as copper or another metal. The use of the central marker **2212** can be advantageous because it allows the location of the piercing point to be directly identified in the image data, rather than indirectly calculated from the locations of other markers (e.g., the markers **2206**). Although FIG. **22**A depicts the phantom **2202***b* as including the central marker **2212** together with the markers **2206** at the first and second ends **2208**, **2210**, of the substrate **2204**, in other embodiments, the markers **2206** can be omitted such that the central marker **2212** is the only marker within the phantom **2202***b*.

[0212] FIG. **22**C is a perspective view of an assembly **2214** that can be used to form the phantom **2202***b*, in accordance with embodiments of the present technology. The assembly **2214** includes an elongate shaft **2216** (e.g., rod, peg, tube, etc.) carrying the central marker **2212**. The elongate shaft **2216** can be formed via additive manufacturing (e.g., 3D printing) with a recess for receiving the central marker **2212**, or the central marker **2212** can be deposited or otherwise formed at the appropriate location in the elongate shaft **2216** during the additive manufacturing process.

[0213] The elongate shaft **2216** can be connected to a first disk **2218** and a second disk **2220**. The first and second disks **2218**, **2220** can be located at or near the opposite ends of the elongate shaft **2216**. The first and second disks **2218**, **2220** can be integrally formed with the elongate shaft **2216** as a single unitary component (e.g., via additive manufacturing). Alternatively, the first and second disks **2218**, **2220** can be discrete components that are coupled to the elongate shaft **2216** via fasteners, adhesives, bonding, etc. For example, the first and second disks **2218**, **2220** can each

include a central hole, and the ends of the elongate shaft **2216** can fit into the holes to form the assembly **2214**.

[0214] Referring to FIGS. **22**B and **22**C together, to assemble the phantom **2202***b*, the elongate shaft **2216** can be positioned into the hollow interior cavity of the substrate **2204**. The elongate shaft **2216** can have a length identical or similar to the length of the substrate **2204** so that the elongate shaft **2216** extends from the first end **2208** of the substrate **2204** to the second end **2210** of the substrate **2204**. In embodiments where the first and second disks **2218**, **2220** are separable from the elongate shaft **2216**, the first and second disks **2218**, **2220** can then be positioned over the first and second ends **2208**, **2210** of the substrate **2204**, respectively, and connected to the elongate shaft **2216**. The first and second disks **2218**, **2220** can be sized to partially or fully cover the first and second ends **2208**, **2210** of the substrate **2204**. For example, the first and second disks **2218**, **2220** can each have a diameter identical or similar to the diameter of the first and second ends **2208**, **2210**, respectively. Optionally, the first and second disks **2218**, **2220** can be attached to the substrate **2204** using fasteners (e.g., snaps), adhesives (e.g., tape), or any other suitable technique to ensure that the central marker **2212** is positioned at the center of the phantom **2202***b*.

[0215] FIG. **22**D is a perspective view of a fiducial marker phantom **2202***c* configured in accordance with embodiments of the present technology. The phantom **2202***c* can be generally similar to the phantom **2202***b* of FIG. **22**A, except that the phantom **2202***b* includes rings **2222** rather than individual markers at the first and second ends **2208**, **2210** of the substrate **2204**. In certain situations, continuous structures such as rings **2222** may be easier to identify in projection images than discrete markers, which can improve the accuracy of the calibration process. The rings **2222** can be made of a radiodense or radiopaque (e.g., metallic) material. The rings **2222** can have a diameter identical or similar to the diameter of the substrate **2204**, and can have a thickness within a range from 1 mm to 5 mm. The rings **2222** can be formed in many different ways. For example, the rings **2222** can be discrete components that are coupled to the substrate **2204** to form the phantom **2202***c*. In such embodiments, the first and second ends **2208**, **2210** of the substrate **2204** can include grooves for receiving the rings **2222**. Alternatively, the rings **2222** can be integrally formed with the substrate **2204**, such as by using an additive manufacturing process in which material is deposited into the substrate **2204** at the appropriate locations.

[0216] Referring again to FIG. **20**, the various steps of the method **2000** can be performed at different times before and/or during an imaging procedure. For example, the distortion correction process of blocks **2002** and **2004** can be performed before an imaging apparatus is used for mrCBCT imaging for the first time. The distortion correction parameters determined in block **2004** can be reused for subsequent mrCBCT procedures performed using the same imaging apparatus, such that the distortion correction process does not need to be performed again. For example, the distortion correction parameters can be interpolated or extrapolated to subsequent images, e.g., using an IMU or other sensor to correlate the stored distortion correction parameters at a certain angle of rotation to a similar angle in the subsequent images. In other embodiments, however, the distortion correction process can be performed periodically for the same imaging apparatus (e.g., once every week, month, six months, year, etc.), performed when there are significant changes in the imaging setup (e.g., if the detector is replaced, if the imaging apparatus is moved to a different environment), or can even be performed each time the imaging apparatus is used. Alternatively, in embodiments where little or no image distortion is observed (e.g., when a flat panel detector is used), the distortion correction process of blocks **2002** and **2004** can be omitted entirely.

[0217] Similarly, the geometric calibration process of blocks **2006** and **2008** can be performed before an imaging apparatus is used for mrCBCT imaging for the first time, e.g., after performing distortion correction for the imaging apparatus. The geometric calibration parameters determined in block **2008** can be reused for subsequent mrCBCT procedures performed using the same imaging apparatus, such that the geometric calibration process does not need to be performed again. In other embodiments, however, the geometric calibration process can be performed periodically for the

same imaging apparatus (e.g., once every week, month, six months, year, etc.), performed when there are significant changes in the imaging setup, or can even be performed each time the imaging apparatus is used (e.g., once before a medical procedure is performed). Optionally, the geometric calibration process of blocks **2006** and **2008** may be omitted entirely.

[0218] Referring again to FIG. **19**, at block **1906**, the method **1900** continues with acquiring images and generating a 3D reconstruction from the images. As described elsewhere herein, the process of block **1906** can be used to perform intraprocedural mrCBCT imaging of a target in the patient anatomy using a manually-operated imaging apparatus that lacks any motors, actuators, etc., for automatically rotating the imaging arm. A representative example of an image acquisition and reconstruction method that can be performed as part of the imaging process of block **1906** is described below with reference to FIGS. **21**A and **21**B.

[0219] FIG. **23**A is a block diagram illustrating a method **2300** for imaging an anatomic region, in accordance with embodiments of the present technology. Some or all of the steps of the method **2300** can be performed as part of the image acquisition and reconstruction process of block **1906** of the method **1900** of FIG. **19**. The method **2300** begins at block **2302** with manually rotating an imaging arm to a plurality of different poses. As previously described, the imaging arm can be part of an imaging apparatus, such as the imaging apparatus **104** of FIG. **1**A. For example, the imaging apparatus can be a mobile C-arm apparatus, and the imaging arm can be the C-arm of the mobile C-arm apparatus. The imaging arm can be rotated around a target anatomic region of a patient along any suitable direction, such as a propeller rotation direction. In some embodiments, the imaging arm is manually rotated to a plurality of different poses (e.g., angles) relative to the target anatomic region. The imaging arm can be rotated through an arc that is sufficiently large for performing CBCT imaging. For example, the arc can be at least 90°, 100°, 110°, 120°, 130°, 140°, 150°, 160°, 170°, 180°, 190°, 200°, 210°, 220°, 230°, 240°, 250°, 260°, 270°, 280°, 290°, 300°, 310°, 320°, 330°, 340°, 350°, or 360°.

[0220] At block **2304**, the method **2300** continues with receiving a plurality of images obtained during the manual rotation. The images can be 2D projection images generated by a detector (e.g., an image intensifier or flat panel detector) carried by the imaging arm. The method **2300** can include generating any suitable number of images, such as at least 50, 100, 200, 300, 400, 500, 600, 700, 800, 900, or 1000 images. The images can be generated at a rate of at least 5 images per second, 10 images per second, 20 images per second, 30 images per second, 40 images per second, 50 images per second, or 60 images per second. In some embodiments, the images are generated while the imaging arm is manually rotated through the plurality of different poses, such that some or all of the images are obtained at different poses of the imaging arm.

[0221] At block **2306**, the method **2300** can include receiving pose data of the imaging arm during the manual rotation. The pose data can be generated using any of the techniques and devices described herein. For example, the pose data can be generated based on sensor data from at least one sensor, such as an IMU or another motion sensor coupled to the imaging arm (e.g., to the detector), to the support arm, or a combination thereof. The sensor data can be processed to determine the pose of the imaging arm at various times during the manual rotation. As previously discussed, the pose of the imaging arm can be estimated without using a fiducial marker board or other reference object positioned near the patient. In other embodiments, however, the pose data can be determined using a fiducial marker board, such as the embodiments described above with reference to FIGS. **18**A-**18**E. In such embodiments, the fiducial marker board can be positioned on the operating table at a known spatial configuration relative to the imaging apparatus (e.g., the same spatial configuration used during calibration).

[0222] Optionally, the pose data of block **2306** can also be used to provide feedback to the user on the speed, smoothness, and/or other characteristics of the manual rotation. For example, if the imaging arm is being rotated too slowly (e.g., if the estimated total rotation time would take longer than 30 seconds and/or would exceed an automatic shut-off time for the imaging apparatus), then

the computing device could output an alert (e.g., an image, text, sound, etc.) instructing the user to increase the rotation speed. Conversely, if the imaging arm is being rotated too quickly, the alert could instruct the user to slow down. As another example, the computing device could display a target speed value or range for image acquisition, as well as the actual speed of the imaging arm. The target speed value or range can be based on a predetermined total rotation time for improved image quality, such as a rotation time within a range from 1 second to 20 seconds. In some embodiments, a graphical representation of the rotation speed is displayed to give the operator real-time feedback during the rotation, e.g., to increase, decrease, or maintain the current rotation speed. For example, the representation can show a first indicator when the rotation is at an appropriate speed, a second indicator (e.g. a red indicator) when the speed is too fast, a third indicator (e.g., a green indicator) when the speed is too slow, etc.

[0223] At block **2308**, the method **2300** includes generating a 3D reconstruction based on the images received in block **2304** and the pose data received in block **2306**. The 3D reconstruction process can include inputting the images into an image reconstruction algorithm, such as a filtered backprojection algorithm, iterative reconstruction algorithm, or other suitable algorithm known to those of skill in the art. Optionally, the images can be processed before being input into the algorithm, e.g., by applying calibration parameters to remove distortion artifacts, correct misalignment, and/or other adjustments to prepare the images for reconstruction. A representative example of method for generating a 3D reconstruction is discussed below in connection with FIG. **23**B.

[0224] FIG. **23**B is a flow diagram illustrating a method **2320** for generating a 3D reconstruction from a plurality of images, in accordance with embodiments of the present technology. Some or all of the processes of the method **2320** can be performed as part of block **2308** of the method **2300** of FIG. **23**A. The method **2320** begins at block **2312** with associating each image with pose data. As discussed above, the pose data can be temporally synchronized with the projection images generated by the imaging apparatus, such that each image is associated with a corresponding pose (e.g., rotational angle) of the imaging arm at or near the time the image was obtained.

[0225] At block **2314**, the method **2320** can include applying one or more distortion correction parameters to some or all of the images. As discussed above, the distortion correction parameters can be applied to the images in order to reduce or eliminate distortion present in the images, e.g., due to use of an image intensifier. The distortion correction parameters can be parameters that were determined in a previous calibration process (e.g., the process of block **2004** of FIG. **20**). In some embodiments, the distortion correction parameters are stored as a lookup table (or similar data structure) that records a set of parameters for each angle of the imaging arm. Accordingly, to correct distortion in a particular image, the angle of the imaging arm at the time of image acquisition ("target angle") can be determined using any of the techniques described herein. The stored distortion correction parameters corresponding to the target angle can then be retrieved from the lookup table. If the target angle does not match any of the entries in the lookup table, the distortion correction parameters can be interpolated or extrapolated from other parameters, e.g., the stored distortion correction parameters for the angle(s) closest to the target angle.

[0226] At block **2316**, the method **2320** can include applying one or more geometric calibration parameters to some or all of the images. As discussed above, the geometric correction parameters can be applied to the images in order to correct any misalignments present in the images, e.g., due to motions of the imaging arm that deviate from a single plane, isocentric trajectory. The distortion correction parameters can be parameters that were determined in a previous calibration process (e.g., the process of block **2008** of FIG. **20**). In some embodiments, the geometric calibration parameters are stored as a lookup table (or similar data structure) that records a set of parameters for each angle of the imaging arm. Accordingly, when adjusting a particular image, the angle of the imaging arm at the time of image acquisition ("target angle") can be determined using any of the techniques described herein. The stored geometric calibration parameters corresponding to the

target angle can then be retrieved from the lookup table. If the target angle does not match any of the entries in the lookup table, the geometric calibration parameters can be interpolated or extrapolated from other parameters, e.g., the stored geometric calibration for the angle(s) closest to the target angle. The geometric calibration parameters can therefore be used to correct the images in situations where it is not feasible to use a fiducial marker phantom or other physical calibration reference.

[0227] In some embodiments, the distortion correction parameters of block **2314** and/or the geometric calibration parameters of block **2316** are adjusted based on the pose data of the imaging arm. These adjustments can be made to account for any deviations from the calibration setup. For example, the actual rotation trajectory of the imaging arm during patient imaging ("imaging trajectory") can differ from the rotation trajectory of the imaging apparatus when determining the calibration parameters for the imaging apparatus as discussed with respect to FIG. **20** ("calibration trajectory"). If the imaging trajectory deviates significantly from the calibration trajectory, the original parameters may no longer be sufficient for correcting image distortion and/or image misalignment.

[0228] Accordingly, the method **2320** can further including detecting whether the imaging trajectory deviates significantly from the calibration trajectory, e.g., with respect to tilt, pitch, roll, or any other suitable measurement value. A deviation can be considered significant, for example, if the magnitude of the difference in the value in the calibration trajectory and the value in the imaging trajectory is at least 5%, 10%, 15%, 20%, 25%, or 50% of the value in the calibration trajectory. The deviations can be detected by comparing the pose data of the imaging apparatus during the imaging trajectory (e.g., the pose data of block **2306** of FIG. **23**A) to the pose data of the imaging apparatus during the calibration trajectory (e.g., the pose data determined during the method **2000** of FIG. **20**).

[0229] If significant deviations are detected, the method **2320** can include updating or otherwise modifying the distortion correction parameters and/or geometric calibration parameters to account for these deviations. The updates can be made to the distortion correction parameters only, to the geometric calibration parameters only, or to both sets of parameters. The updates can be determined based on the pose data of the imaging arm and the known geometry of the imaging apparatus, in accordance with techniques known to those of skill in the art. For example, if the imaging arm exhibited a forward tilt of 1.5° at the 90° angular position in the calibration trajectory, but exhibited a forward tilt of 2.0° at the 90° angular position in the imaging trajectory, the geometric calibration parameters for the image(s) obtained at or near the 90° angular position can be updated to compensate for the difference in the forward tilt. The updated geometric calibration parameters can be computed by determining how the detected deviation affects the geometry of the imaging apparatus (e.g., with respect to piercing point, skewness, pitch, roll, tilt, and/or source-to-detector distance), determining the amount and/or direction of additional image misalignment produced by the change in geometry, and then determining the parameters that would correct the additional misalignment.

[0230] At block **2318**, the method **2320** can continue with generating a 3D reconstruction from the images, in accordance with techniques known to those of skill in the art. For example, the 3D reconstruction can be generated using filtered backprojection, iterative reconstruction, and/or other suitable algorithms. Optionally, image interpolation can also be applied to the reconstruction process to reduce image noise arising from a reduced number of image acquisition angles, if appropriate.

[0231] The method **2320** of FIG. **23**B can be modified in many different ways, if desired. For example, in other embodiments, block **2314** can be omitted, e.g., if the imaging apparatus uses a flat panel detector or otherwise is not expected to produce much image distortion. As another example, block **2316** can be omitted, if the images are not expected to be significantly misaligned. Additionally, the method **2320** can include other image preprocessing steps not shown in FIG. **23**B.

[0232] Referring again to FIG. **23**A, at block **2310**, the method **2300** can optionally include outputting a graphical representation of the 3D reconstruction. The graphical representation can be displayed on an output device (e.g., the display **132** and/or secondary display **134** of FIG. **1**A) to provide guidance to a user in performing a medical procedure. In some embodiments, the graphical representation includes the 3D reconstruction generated in block **2308**, e.g., presented as a 3D model or other virtual rendering. Alternatively or in combination, the graphical representation can include 2D images derived from the 3D reconstruction (e.g., 2D axial, coronal, and/or sagittal slices).

[0233] In some embodiments, the user views the graphical representation to confirm whether a medical tool is positioned at a target location. For example, the graphical representation can be used to verify whether a biopsy instrument is positioned within a nodule or lesion of interest. As another example, the graphical representation can be used to determine whether an ablation device is positioned at or near the tissue to be ablated. If the tool is positioned properly, the user can proceed with performing the medical procedure. If the graphical representation indicates that the tool is not at the target location, the user can reposition the tool, and then repeat some or all of the steps of the method **2300** to generate a new 3D reconstruction of the tool and/or target within the anatomy.

[0234] Referring again to FIG. **19**, the method **1900** can optionally include additional processes not shown in FIG. **19**. For example, once the calibration process of block **1904** has been completed, the method **1900** can optionally include performing a pre-acquisition rotation of the imaging arm. The pre-acquisition rotation can serve as a "practice" rotation in order to provide feedback to the user on the trajectory and quality of the manual rotation. The feedback can be used to adjust the stabilization, trajectory, speed, quality, and/or other aspects of the manual rotation and/or imaging apparatus setup. In some embodiments, some or all of the processes related to the pre-acquisition rotation are performed without any radiation to reduce the patient's radiation exposure. A representative example of a method that can be performed as part of a pre-acquisition process is described below with reference to FIG. **24**.

[0235] FIG. **24** is a flow diagram illustrating a method **2400** of preparing an imaging apparatus for image acquisition, in accordance with embodiments of the present technology. The method **2400** can be performed before the image acquisition and reconstruction process of block **1906** of FIG. **19**. The method **2400** can begin at block **2402**, with aligning the field of view of the imaging apparatus with a target in the anatomic region. In some embodiments, the field of view in the 3D reconstruction is significantly smaller than the field of view in the projection images. Accordingly, the alignment process of block **2402** can be performed to ensure that the target site will be visible in the final CBCT images. In some embodiments, the alignment process is performed after the imaging apparatus has been stabilized and/or calibrated. In other embodiments, however, the alignment process of block **2402** is optional and may be omitted.

[0236] In some embodiments, the alignment process of block **2402** includes obtaining one or more test images of the patient anatomy, such as a lateral and/or frontal projection image. The computing device can then process the test images to identify the image locations that would be present in the image reconstruction. For example, the computing device can overlay an indicator (e.g., a circle or other shape, shading, arrows) onto the test images that represents the smaller field of view of the image reconstruction. As another example, the computing device can crop or otherwise remove portions of the test images to remove locations that would not be visible in the image reconstruction. Accordingly, the user can view the processed test images to determine whether the target will be visible in the image reconstruction. If the target will not be visible, the operator can adjust the positioning of the imaging apparatus and/or patient, and can acquire new test images.

[0237] At block **2404**, the method can continue with manually rotating the imaging arm of the imaging apparatus to a plurality of different poses. The manual rotation can be performed under conditions identical or similar to the conditions during which the actual image acquisition will take

place. For example, the imaging apparatus can already be stabilized, calibrated, and/or aligned as discussed above. The user can rotate the imaging arm along the rotational trajectory that will be used to generate the actual images, such as a propeller rotation over a range of at least 90°, 100°, 110°, 120°, 130°, 140°, 150°, 160°, 170°, 180°, 190°, 200°, 210°, 220°, 230°, 240°, 250°, 260°, 270°, 280°, 290°, 300°, 310°, 320°, 330°, 340°, 350°, or 360°.

[0238] At block **2406**, the method **2400** continues with receiving pose data of the imaging arm during the manual rotation of block **2404**. The pose data can be generated using any of the devices and techniques described herein. For example, the pose of the imaging arm can be determined using a motion sensor coupled to the imaging arm. The pose data can be transmitted to a suitable computing device (e.g., the computing device **130** of FIG. **1**A) for storage and processing.

[0239] At block **2408**, the method **2400** can include comparing the pose data of block **2406** to calibration pose data. The calibration pose data can include pose data of the imaging arm during a manual rotation performed as part of a previous calibration process (e.g., the geometric calibration process of FIG. **20**). The calibration pose data can indicate the trajectory and/or speed of the imaging arm during the previous calibration rotation. In some embodiments, the characteristics of the manual rotation performed by the user during the actual image acquisition should be as close as possible to the characteristics of the calibration rotation to improve the quality of the image reconstruction. Accordingly, in block **2408**, the computing device can analyze the pose data to determine whether the pre-acquisition rotation deviates significantly from the calibration rotation with respect to trajectory, speed, stabilization (e.g., absence of oscillations, shifts, or other unwanted motions), etc.

[0240] At block **2410**, the method **2400** can include generating feedback and/or making adjustments to the imaging apparatus, based on the comparison performed in block **2408**. For example, the computing device can provide feedback to the user about how the pre-acquisition rotation deviates from the calibration rotation. The computing device can also provide recommendations on how to adjust the rotation and/or imaging apparatus to more closely conform to the calibration rotation or otherwise improve the operation of the imaging apparatus. For example, if the imaging apparatus was not as well stabilized in the pre-acquisition rotation compared to the calibration rotation, the user can adjust the stabilization techniques used to improve stability, e.g., by adding more shim structures, changing the types and/or locations of the shim structures, altering where force is applied during the rotation, or any of the other approaches described herein. As another example, if the imaging arm is tilted or otherwise positioned in a way that differs from the positioning in the calibration rotation, the computing device can recommend that the user adjust the imaging arm accordingly. In yet another example, the feedback can also indicate whether the pre-acquisition rotation was sufficiently smooth, uniform (e.g., circular), and/or at the appropriate speed for image acquisition purposes.

[0241] In some embodiments, the computing device can output a graphical user interface to guide the operator in making the appropriate adjustments. For example, the interface can show a virtual representation of the imaging apparatus with indicators (e.g., arrows) displaying the recommended adjustments. Alternatively or in combination, the interface can output textual instructions describing the adjustments to the imaging apparatus and/or rotational trajectory to be made. In some embodiments, the interface displays real-time feedback, such as the actual position and/or orientation of the imaging arm (e.g., from IMU and/or other sensor data) as the user makes adjustments so the user can see whether the targeted position and/or orientation has been reached. Optionally, the interface can also output alerts, warnings, or other feedback during the manual rotation (e.g., "rotation is too fast," "imaging arm is too far to the left") so the user can adjust the rotation trajectory and/or speed in real-time.

[0242] The method **2400** of FIG. **24** can be modified in many different ways, if desired. For example, some or all of the processes of the method **2400** can be performed multiple times, e.g., to ensure that the user is performing the manual rotation appropriately and/or that the imaging

apparatus is properly set up for acquiring images of the target. In some embodiments, some or all of the processes of blocks **2404**, **2406**, **2408**, and/or **2410** are repeated until the pre-acquisition rotation is sufficiently close to the calibration rotation. As another example, the process of acquiring and reviewing test images in block **2402** can be repeated until the user confirms that the target is properly aligned for image reconstruction purposes. Moreover, some or all of the processes of the method **2400** can be omitted, such as the processes of blocks **2402** and/or **2410**.

[0243] Referring again to FIG. **19**, the method **1900** can be modified in many different ways. For example, the processes of the method **1900** can be performed in a different order. In some embodiments, stabilization may not be necessary to accurately determine the calibration parameters and/or to perform the pre-acquisition rotation. Accordingly, the stabilization process of block **1902** can be performed after the calibration process of block **1904**. Moreover, some of the processes of the method **1900** can be optional. For example, any of the processes of blocks **1902** and/or **1904** can be omitted from the method **1900**.

[0244] FIG. **25**A is a flow diagram illustrating a method **2500** for calibration and image acquisition using a fiducial marker board, in accordance with embodiments of the present technology. The method **2500** can be generally similar to the method **1900** of FIG. **19**, except that a fiducial marker board is used to estimate the pose (e.g., rotational angle) of the imaging arm during geometric calibration and image acquisition.

[0245] The method **2500** begins at block **2502** with attaching a fiducial marker phantom to a fiducial marker board. The fiducial marker phantom can be any of the embodiments described with respect to FIGS. **22**A-**22**D, and the fiducial marker board can be any of the embodiments described with respect to FIGS. **18**A-**18**G.

[0246] At block **2504**, the method **2500** can include obtaining a set of first images of the fiducial marker phantom and fiducial marker board. The first images can be 2D projection images acquired by the detector as the imaging arm is manually rotated through a plurality of different poses (e.g., rotation angles), as described elsewhere herein. Each first image can be associated with a corresponding pose of the imaging arm. The pose of the imaging arm can be determined from the markers of the fiducial marker board in the first images, as described above with respect to FIGS. **18**A-**18**G.

[0247] At block **2506**, the method **2500** continues with determining a set of geometric calibration parameters based on the first images. The geometric calibration parameters can be determined by identifying the locations of the fiducial markers of the phantom in the first images, as discussed above with respect to block **2006** of the method **2000** of FIG. **20**. In some embodiments, the combination of the phantom with the fiducial marker board allows the geometry of the imaging apparatus (e.g., piercing point, skewness, pitch, roll, tilt, source-to-detector distance) to be fully determined.

[0248] At block **2508**, the method **2500** can include removing the fiducial marker phantom from the fiducial marker board and positioning a patient on the fiducial marker board. For example, the patient can be placed in a supine position with their back resting on the board.

[0249] At block **2510**, the method **2500** continues with obtaining a set of second images of the fiducial marker board and the patient. The second images can be 2D projection images acquired by the detector as the imaging arm is manually rotated through a plurality of different poses (e.g., rotation angles), as described elsewhere herein. Each second image can be associated with a corresponding pose of the imaging arm. The pose of the imaging arm can be determined from the markers of the fiducial marker board in the second images, as described above with respect to FIGS. **18**A-**18**G.

[0250] At block **2512**, the method **2500** can include applying the geometric calibration parameters to some or all of the second images. The process of block **2512** can be identical or similar to the process of block **2316** of the method **2320** of FIG. **23**B. For example, in some embodiments, the geometric calibration parameters of block **2306** are retrieved from a lookup table (or similar data

structure) based on the pose (e.g., rotational angle) of the imaging arm, as determined using the fiducial marker board. Because the same fiducial marker board is used for both geometric calibration and image acquisition, the pose estimates generated from the fiducial marker board are consistent across these processes and can therefore be used to determine the appropriate geometric calibration parameters to be applied to each second image.

[0251] At block **2514**, the method **2500** can include generating a 3D reconstruction based on the second images. The 3D reconstruction can be produced from the second images using any of the techniques described elsewhere herein. Optionally, before the 3D reconstruction is generated, the markers of the fiducial marker board and/or any imaging artifacts produced by the markers can be subtracted from the second images. The subtraction can be performed using computer vision techniques and/or other image processing algorithms known to those of skill in the art.

[0252] FIG. **25**B is a flow diagram illustrating a method for operating an imaging apparatus, in accordance with embodiments of the present technology. At block **2502′**, the method **2500′** can include positioning a phantom (e.g., a calibration phantom and/or cylinder) near the imaging apparatus. For example, the phantom can be positioned near an axis of rotation of an imaging arm of the imaging apparatus. At block **2504′**, the method can include obtaining first 2D images using a shim-stabilized imaging arm at multiple angles. At block **2506′**, the method **2500′** can include obtaining pose data of the imaging arm based on the first images that include the phantom. In some embodiments, a general model of the pose of the imaging arm can be created for any arbitrary projection angle. At block **2508′**, the method **2500′** can include removing the phantom from the center of rotation and place a fiducial marker board around a patient area of interest. In some embodiments, the fiducial marker board is an L- or J-shaped fiducial marker board. In other embodiments, the fiducial marker board is not an L- or J-shaped fiducial marker board. At block **2510′**, the method **2500′** can include obtaining second 2D images of both the fiducial marker board and the patient during a rotation of the imaging arm at multiple angles. At block **2512′**, the method **2500′** can include obtaining second pose data of the imaging arm based on the second images. For example, the method **2500′** can include estimating an imaging arm angle for each of the second images using the known geometric arrangement of the fiducial marker board. The method **2500′** can include using the angle estimation from the fiducial marker board to reference the general calibration model generated from the first images to determine the imaging arm pose and other relevant geometric information for each of the second images. The method **2500′** can include removing the signal of the fiducial markers in the fiducial marker board. At block **2514′**, the method **2500′** can include generating a 3D reconstruction of the image volume using the second images with the estimated pose information determined using the angle estimation from the fiducial marker board.

[0253] In some embodiments of the present technology, a specialized fiducial board, such as an L- or J-shaped fiducial marker board or other fiducial marker board, can be used in conjunction with a phantom (e.g., a calibration phantom and/or cylinder) to perform manually rotated 3D reconstructions. In such embodiments, the phantom can be configured to determine the pose of the imaging arm using methods known to those skilled in the art. In some embodiments of the methods herein, the phantom can be placed near the center of the imaging arm axis of rotation and a first series of 2D images is acquired using a shim-stabilized imaging arm at multiple angles. The pose of the imaging arm at each image angle can be determined from the corresponding 2D image by tracking and/or segmenting the fiducial markers in the phantom as known to those skilled in the art. Once the pose of the imaging arm at each image is determined, a general model of the pose of the imaging arm can be created for any arbitrary projection angle using interpolation/extrapolation techniques known to those skilled in the art.

[0254] Subsequently, the phantom is removed and a patient area of interest (e.g., a chest) can be placed near the imaging arm (such as the isocenter of a C-arm). A fiducial marker board, such as an L- or J-shaped fiducial marker board can be placed around the patient near the area of interest. The

fiducial marker board has an arrangement of radiodense ball bearings or other markers from which the angular position of the imaging arm can be determined using methods known to those skilled in the art. A second series of 2D images of both the fiducial marker board and the patient can then be obtained during a rotation of the imaging arm at multiple angles. The fiducial markers in the board can then be automatically tracked and segmented using their known pattern. The encoding of the fiducial pattern index allows for estimation of the imaging arm angle for each 2D projection image during the second series of images. Once the angle is estimated for each image of the second series of images, the estimated angle can be used to reference the general calibration model (e.g., a lookup table, etc.) generated from the first series of images. The angle determined from each image in the second series of images is thus used to determine the correct pose and other relevant geometric information of the C-arm as modeled from the first series of images. Once the pose of the C-arm is determined, then the signals of the fiducial markers in the board can be virtually (digitally) removed or suppressed from each projection image using techniques known to those of skill in the art (e.g. interpolation of pixel neighbors) to limit or prevent metal artifacts within the reconstructed 3D images of the patient. Once the signal from the fiducial markers is removed, a 3D reconstruction can be performed.

[0255] FIGS. **26**A and **26**B are representative CBCT images of a phantom generated using a manually-rotated mobile C-arm apparatus. The images were acquired using a GE Healthcare OEC 9900 C-arm apparatus with an image intensifier and a rotation angle of approximately 180 degrees. The phantom was a cylindrical phantom including a set of rings and a central marker, similar to the phantom **2202**c of FIG. **22**D. The images are cross-section views of the phantom showing the outer edge of the cylinder and the shaft carrying the central marker (the central marker is not shown in the images). The image in FIG. **26**A was generated without using calibration or shim stabilization, while the image in FIG. **26**B was generated with calibration and shim stabilization, in accordance with embodiments of the present technology. As shown in FIG. **26**A, in the absence of calibration and shim stabilization, the image is blurry, misaligned, and includes significant distortion artifacts. In contrast, after calibration and shim stabilization, the image of FIG. **26**B accurately and clearly depicts the geometry of the phantom.

[0256] FIGS. **27**A and **27**B are representative CBCT images of a lung generated using a manually-rotated mobile C-arm apparatus. The images were acquired using a GE Healthcare OEC 9900 C-arm apparatus with an image intensifier and a rotation angle of approximately 180°, and show a live porcine chest with an implanted pulmonary nodule **2702**. The image in FIG. **27**A was generated without using calibration or shim stabilization, while the image in FIG. **27**B was generated with calibration and shim stabilization, in accordance with embodiments of the present technology. As shown in FIG. **27**A, without calibration and shim stabilization, the anatomic structures are not visible in the resulting image. As shown in FIG. **27**B, with calibration and shim stabilization, the resulting image has sufficiently high spatial resolution and contrast-to-noise ratio to clearly depict the anatomic structures within and near the lung, such as the nodule **2702** blood vessel **2704**, bronchi **2706**, and rib **2708**.

[0257] FIG. **27**C is a CBCT image generated using a robotically-rotated CBCT imaging system. Specifically, the image was acquired using a Siemens Artis Zeego CBCT system, a stationary system with a motorized imaging arm, with a rotation angle of approximately 220°. The image shows the same porcine chest as the images of FIGS. **27**A and **27**B. As can be seen by comparing FIGS. **27**B and **27**C, the imaging techniques described herein can produce image reconstructions using a manually-operated C-arm apparatus that are comparable in quality to image reconstructions produced by high-end, specialized CBCT systems.

EXAMPLES

[0258] The following examples are included to further describe some aspects of the present technology, and should not be used to limit the scope of the technology. [0259] 1. A method for imaging an anatomic region, the method comprising: [0260] receiving, from a detector carried by

an imaging arm of an x-ray imaging apparatus, a plurality of two-dimensional (2D) images of the anatomic region, wherein the 2D images are obtained during manual rotation of the imaging arm, and wherein the imaging arm is stabilized by a shim structure during the manual rotation; [0261] receiving, from at least one sensor coupled to the imaging arm, sensor data indicative of a plurality of poses of the imaging arm during the manual rotation; and [0262] generating, based on the 2D images and the sensor data, a 3D representation of the anatomic region. [0263] 2. The method of Example 1, wherein the x-ray imaging apparatus comprises a mobile C-arm apparatus. [0264] 3. The method of Example 1 or 2, wherein the detector comprises an image intensifier. [0265] 4. The method of any one of Examples 1 to 3, wherein the x-ray imaging apparatus comprises a support arm slidably coupled to the imaging arm, and the shim structure is positioned at an interface between the imaging arm and the support arm. [0266] 5. The method of Example 4, wherein the shim structure is configured to reduce movement of the imaging arm relative to the support arm. [0267] 6. The method of Example 4 or 5, wherein the support arm is rotatably coupled to a movable base, and the support arm and the imaging arm are manually rotated relative to the movable base to obtain the 2D images. [0268] 7. The method of Example 6, wherein the manual rotation is actuated by a force applied at or near an interface between the support arm and the movable base. [0269] 8. The method of Example 7, wherein the force is applied to a lever structure coupled at or near the interface between the support arm and the movable base. [0270] 9. The method of any one of Examples 4 to 8, wherein the shim structure comprises at least one elongate member configured to fit at least partially in the interface between the imaging arm and the support arm. [0271] 10. The method of Example 9, wherein the shim structure includes: [0272] a set of elongate members positioned at two sides of the interface between the imaging arm and the support arm, and [0273] a bridge region connecting the set of elongate members. [0274] 11. The method of any one of Examples 1 to 10, wherein the manual rotation comprises a propeller rotation. [0275] 12. The method of any one of Examples 1 to 11, wherein the manual rotation comprises a rotation of at least 90 degrees. [0276] 13. The method of Example 12, wherein the manual rotation comprises a rotation of at least 180 degrees. [0277] 14. The method of any one of Examples 1 to 13, wherein the at least one sensor comprises a motion sensor and the sensor data comprises motion data of the imaging arm. [0278] 15. The method of Example 14, wherein the motion sensor comprises an inertial measurement unit (IMU). [0279] 16. The method of Example 14 or 15, further comprising determining the plurality of poses of the imaging arm based on the motion data. [0280] 17. The method of any one of Examples 1 to 16, wherein the at least one sensor includes a sensor coupled to the detector. [0281] 18. The method of any one of Examples 1 to 17, wherein generating the 3D representation comprises associating each 2D image with a corresponding pose of the imaging arm. [0282] 19. The method of Example 18, wherein associating each 2D image with the corresponding pose comprises identifying a pose of the imaging arm when the 2D image was obtained. [0283] 20. The method of any one of Examples 1 to 19, further comprising applying one or more distortion correction parameters to at least some of the 2D images before generating the 3D representation. [0284] 21. The method of any one of Examples 1 to 20, further comprising applying one or more geometric calibration parameters to at least some of the 2D images before generating the 3D representation. [0285] 22. The method of any one of Examples 1 to 21, further comprising outputting real-time feedback to an operator during the manual rotation for adjusting a rotation speed of the imaging arm. [0286] 23 The method of any one of Examples 1 to 22, further comprising outputting the 3D representation on a graphical user interface during a medical procedure performed in the anatomic region. [0287] 24. A system for imaging an anatomic region, the system comprising: [0288] a shim structure configured to stabilize manual rotation of an imaging arm of an x-ray imaging apparatus; [0289] at least one sensor configured to generate sensor data indicative of a pose of the imaging arm; [0290] one or more processors operably coupled to the x-ray imaging apparatus and the at least one sensor; and [0291] a memory operably coupled to the one or more processors and storing instructions that, when executed by the one or

more processors, cause the system to perform operations comprising: [0292] receiving, from the x-ray imaging apparatus, a sequence of two-dimensional (2D) images of the anatomic region obtained during the manual rotation of the imaging arm; [0293] determining, based on the sensor data, pose information of the imaging arm during the manual rotation of the imaging arm; and [0294] generating, based on the 2D images and the pose information, a 3D reconstruction of the anatomic region. [0295] 25. The system of Example 24, wherein the x-ray imaging apparatus comprises a mobile C-arm apparatus. [0296] 26. The system of Example 24 or 25, wherein the x-ray imaging apparatus comprises a support arm slidably coupled to the imaging arm, and the shim structure is configured to be positioned at an interface between the imaging arm and the support arm. [0297] 27. The system of Example 26, wherein the shim structure is configured to reduce movement of the imaging arm relative to the support arm. [0298] 28. The system of Example 27, wherein the shim structure inhibits orbital rotation of the imaging arm. [0299] 29 The system of any one of Examples 26 to 28, wherein the support arm is rotatably coupled to a movable base, and the support arm and the imaging arm are manually rotated relative to the movable base to obtain the 2D images. [0300] 30. The system of Example 29, further comprising a lever structure coupled at or near an interface between the support arm and the movable base, wherein the lever structure is configured to facilitate the manual rotation of the imaging arm. [0301] 31. The system of any one of Examples 26 to 30, wherein the shim structure comprises at least one elongate member configured to fit at least partially in the interface between the imaging arm and the support arm. [0302] 32. The system of Example 31, wherein the shim structure includes a pair of arm regions positioned at two sides of the interface between the imaging arm and the support arm. [0303] 33 The system of Example 32, wherein the shim structure includes a bridge region connecting the pair of arm regions. [0304] 34 The system of any one of Examples 24 to 33, wherein the manual rotation comprises an angular rotation. [0305] 35. The system of any one of Examples 24 to 34, wherein the manual rotation comprises a rotation of at least 90 degrees. [0306] 36. The system of any one of Examples 24 to 35, wherein the at least one sensor comprises a motion sensor and the sensor data comprises motion data of the imaging arm. [0307] 37. The system of Example 36, wherein the motion sensor comprises an inertial measurement unit (IMU). [0308] 38. The system of Example 36 or 37, wherein the motion sensor is coupled to the detector. [0309] 39 The system of Example 38, wherein the motion sensor is coupled to the detector via an attachment device. [0310] 40. The system of Example 39, wherein the attachment device comprises a clip, bracket, frame, or container. [0311] 41 The system of any one of Examples 24 to 40, further comprising a controller operably coupled to the at least one sensor, wherein the controller is configured to temporally synchronize the 2D images to the sensor data generated by the at least one sensor. [0312] 42. The system of any one of Examples 24 to 41, further comprising a radiation sensor configured to generate a signal in response to detected radiation, wherein the signal is transmitted to the controller to temporally synchronize the 2D images to the sensor data. [0313] 43. The system of any one of Examples 24 to 42, further comprising a display configured to output a graphical representation of the 3D reconstruction. [0314] 44. A non-transitory computer-readable medium comprising instructions that, when executed by one or more processors of a computing system, cause the computing system to perform operations comprising: [0315] receiving, from a detector carried by an imaging arm of a mobile C-arm apparatus, a plurality of projection images of an anatomic target, wherein the projection images are obtained during manual rotation of the imaging arm, and wherein the imaging arm is stabilized by a shim structure during the manual rotation; [0316] receiving, from at least one sensor coupled to the imaging arm, pose data of the imaging arm during the manual rotation; and generating, based on the projection images and the pose data, a 3D reconstruction of the anatomic target. [0317] 45. A method for imaging an anatomic region, the method comprising: [0318] receiving, from a detector carried by an imaging arm of an x-ray imaging apparatus, a plurality of two-dimensional (2D) images of the anatomic region, wherein the 2D images are obtained during manual rotation of the imaging arm, and wherein the imaging arm is

stabilized by a shim structure during the manual rotation; [0319] receiving pose data of the imaging arm during the manual rotation; and generating, based on the 2D images and the pose data, a 3D representation of the anatomic region. [0320] 46 The method of Example 45, wherein the pose data is generated from images of a fiducial marker board positioned near the anatomic target. [0321] 47. The method of Example 46, wherein the fiducial marker board includes a plurality of fiducial markers and at least some of the fiducial markers are located in different planes. [0322] 48. The method of Example 46 or 47, wherein the fiducial marker board includes a base region and at least one sidewall extending upward from the base region. [0323] 49 The method of any one of Examples 45 to 48, wherein the pose data is generated by at least one sensor coupled to the imaging arm. [0324] 50. A method for operating an imaging apparatus, the method comprising: [0325] receiving, from a detector carried by an imaging arm of the imaging apparatus, a plurality of first images of a set of first fiducial markers, wherein the first images are obtained during manual rotation of the imaging arm; [0326] determining a set of distortion correction parameters for the imaging apparatus based on the first images; [0327] receiving, from the detector, a plurality of second images of a set of second fiducial markers, wherein the second images are obtained during manual rotation of the imaging arm; and [0328] determining a set of geometric calibration parameters for the imaging apparatus based on the second images. [0329] 51. The method of Example 50, wherein the imaging apparatus is a mobile C-arm apparatus. [0330] 52. The method of Example 50 or 51, wherein the first and second images are each obtained during a propeller rotation of the imaging arm. [0331] 53 The method of any one of Examples 50 to 52, wherein the detector comprises an image intensifier. [0332] 54. The method of any one of Examples 50 to 53, wherein the first fiducial markers are arranged in a grid. [0333] 55 The method of any one of Examples 50 to 54, further comprising determining, using at least one sensor carried by the imaging arm, pose data of the imaging arm associated with the first images, wherein the distortion correction parameters are determined based on the pose data. [0334] 56. The method of any one of Examples 50 to 55, wherein the second fiducial markers are disposed within a phantom. [0335] 57. The method of any one of Examples 50 to 56, further comprising adjusting at least some of the second images using the set of distortion correction parameters. [0336] 58. The method of any one of Examples 50 to 57, further comprising determining, using at least one sensor carried by the imaging arm, pose data of the imaging arm associated with the second images, wherein the geometric calibration parameters are determined based on the pose data. [0337] 59. The method of Example 58, further comprising processing the second images to determine one or more of the following: piercing point, skewness, pitch, roll, tilt, or source-to-detector distance of the imaging apparatus. [0338] 60. The method of Example 58 or 59, further comprising: [0339] receiving, from at least one sensor coupled to the imaging arm, second pose data of the imaging arm during a pre-acquisition manual rotation; [0340] comparing the second pose data to the pose data associated with the second images; and outputting feedback to a user based on the comparison. [0341] 61. The method of Example 60, wherein the feedback comprises feedback regarding one or more of the following: rotation trajectory, rotation speed, orientation of the imaging arm, position of the imaging arm, or stability of the imaging arm. [0342] 62. The method of any one of Examples 50 to 61, further comprising: [0343] receiving, from the detector, a plurality of third images of an anatomic region of a patient, wherein the third images are obtained during manual rotation of the imaging arm, and wherein the imaging arm is stabilized by a shim structure during the manual rotation; [0344] receiving, from at least one sensor coupled to the imaging arm, pose data of the imaging arm associated with the third images; and [0345] generating a volumetric reconstruction of the anatomic region based on the third images and the pose data. [0346] 63. The method of Example 62, further comprising: [0347] applying the distortion correction parameters to the third images; and applying the geometric calibration parameters to the third images. [0348] 64 The method of Example 63, further comprising updating one or more of the distortion correction parameters or the geometric calibration parameters based on data from the at least one sensor,

before generating the volumetric reconstruction. [0349] 65. A system for imaging an anatomic region, the system comprising: [0350] one or more processors; and [0351] a memory operably coupled to the one or more processors and storing instructions that, when executed by the one or more processors, cause the system to perform operations comprising: [0352] receiving, from a detector carried by an imaging arm of an x-ray imaging apparatus, a plurality of first images of a fiducial marker grid, wherein the first images are obtained during manual rotation of the imaging arm; [0353] determining a set of distortion correction parameters for the imaging apparatus based on the first images; [0354] receiving, from the detector, a plurality of second images of a fiducial marker phantom, wherein the second images are obtained during manual rotation of the imaging arm; and [0355] determining a set of geometric calibration parameters for the imaging apparatus based on the second images. [0356] 66. The system of Example 65, wherein the x-ray imaging apparatus is a mobile C-arm apparatus. [0357] 67. The system of Example 65 or 66, wherein the first and second images are each obtained during a propeller rotation of the imaging arm. [0358] 68. The system of any one of Examples 65 to 67, wherein the detector comprises an image intensifier. [0359] 69. The system of any one of Examples 65 to 68, further comprising the fiducial marker grid. [0360] 70. The system of Example 69, wherein the fiducial marker grid includes a central portion and a peripheral portion, the central portion having a different pattern than the peripheral portion. [0361] 71. The system of any one of Examples 65 to 70, further comprising an attachment device for mounting the fiducial marker grid to the detector. [0362] 72. The system of Example 71, further comprising a motion sensor, wherein the attachment device is configured to couple the motion sensor to the detector. [0363] 73. The system of any one of Examples 65 to 72, wherein the operations further comprise determining, using the motion sensor, pose data of the imaging arm associated with the first images, wherein the distortion correction parameters are determined based on the pose data. [0364] 74. The system of any one of Examples 65 to 73, further comprising the fiducial marker phantom. [0365] 75. The system of Example 74, wherein the fiducial marker phantom includes at least one second fiducial marker at a central portion of the phantom. [0366] 76. The system of Example 74 or 75, wherein the phantom includes: [0367] a first ring at a first end of the phantom; and [0368] a second ring at a second end of the phantom opposite the first end. [0369] 77. The system of any one of Examples 65 to 76, wherein the operations further comprise adjusting at least some of the second images using the set of distortion correction parameters. [0370] 78. The system of any one of Examples 65 to 77, further comprising a motion sensor coupled to the detector. [0371] 79 The system of Example 78, wherein the operations further comprise determining, using the motion sensor, pose data of the imaging arm associated with the second images, wherein the geometric calibration parameters are determined based on the pose data. [0372] 80. The system of Example 79, wherein the operations further comprise: [0373] receiving, from the motion sensor, second pose data of the imaging arm during a pre-acquisition manual rotation; and comparing the second pose data to the pose data associated with the second images. [0374] 81. The system of Example 80, further comprising a display configured to output feedback to a user based on the comparison of the second pose data to the pose data, wherein the feedback comprises feedback regarding one or more of the following: rotation trajectory, rotation speed, orientation of the imaging arm, position of the imaging arm, or stability of the imaging arm. [0375] 82. The system of any one of Examples 65 to 81, wherein the operations further comprise: [0376] receiving, from the detector, a plurality of third images of an anatomic region of a patient, wherein the third images are obtained during manual rotation of the imaging arm, and wherein the imaging arm is stabilized by a shim structure during the manual rotation; [0377] receiving, from a motion sensor coupled to the detector, pose data of the imaging arm associated with the third images; [0378] adjusting the third images using the distortion correction parameters; [0379] adjusting the third images using the geometric calibration parameters; and [0380] generating a volumetric reconstruction of the anatomic region based on the third images and the pose data. [0381] 83. A non-transitory computer-readable medium comprising instructions that, when

executed by one or more processors of a computing system, cause the computing system to perform operations comprising: [0382] receiving, from a detector carried by an imaging arm of an imaging apparatus, a plurality of first images of a set of first fiducial markers, wherein the first images are obtained during manual rotation of the imaging arm; [0383] determining a set of distortion correction parameters for the imaging apparatus based on the first images; [0384] receiving, from the detector, a plurality of second images of a set of second fiducial markers, wherein the second images are obtained during manual rotation of the imaging arm; and [0385] determining a set of geometric calibration parameters for the imaging apparatus based on the second images. [0386] 84. A method for imaging an anatomic region, the method comprising: [0387] receiving, from a detector carried by an imaging arm of a mobile C-arm apparatus, a plurality of 2D images of the anatomic region, wherein the 2D images are obtained during manual rotation of the imaging arm, and wherein the imaging arm is stabilized by a shim structure during the manual rotation; [0388] receiving data indicative of a plurality of poses of the imaging arm during the manual rotation; and [0389] generating, based on the 2D images and the data, a 3D reconstruction of the anatomic region. [0390] 85. The method of Example 84, wherein the mobile C-arm apparatus comprises a support arm slidably coupled to the imaging arm, and the shim structure is positioned at an interface between the imaging arm and the support arm. [0391] 86. The method of Example 85, wherein the shim structure is configured to reduce movement of the imaging arm relative to the support arm. [0392] 87. The method of Example 84 or Example 85, wherein the shim structure is configured to fit at least partially in the interface between the imaging arm and the support arm. [0393] 88. The method of Example 87, wherein the shim structure includes: [0394] a pair of arm regions configured to be positioned at two sides of the interface between the imaging arm and the support arm, and [0395] a bridge region connecting the set of elongate members. [0396] 89. The method of Example 85, wherein the support arm is rotatably coupled to a movable base, and the support arm and the imaging arm are manually rotated relative to the movable base to obtain the 2D images. [0397] 90. The method of Example 89, wherein the manual rotation is actuated by a force applied to a lever structure coupled at or near an interface between the support arm and the movable base. [0398] 91. The method of any one of Examples 84 to 90, wherein the manual rotation comprises a propeller rotation. [0399] 92. The method of any one of Examples 84 to 91, wherein the manual rotation comprises a rotation of at least 90 degrees. [0400] 93. The method of any one of Examples 84 to 91, wherein the data indicative of the plurality of poses of the imaging arm are received from a motion sensor coupled to the imaging arm. [0401] 94. The method of Example 93, wherein the motion sensor comprises an inertial measurement unit. [0402] 95 The method of any one of Examples 84 to 94, wherein the plurality of 2D images includes a fiducial board, and wherein the data indicative of the plurality of poses of the imaging arm are generated from the 2D images. [0403] 96. The method of any one of Examples 84 to 95, further comprising associating each 2D image with a corresponding pose of the imaging arm at a time when the 2D image was obtained. [0404] 97. The method of any one of Examples 84 to 96, wherein the 3D reconstruction comprises a cone-beam computed tomography reconstruction. [0405] 98 The method of any one of Examples 84 to 97, further comprising applying one or more distortion correction parameters to at least some of the 2D images before generating the 3D reconstruction. [0406] 99 The method of any one of Examples 84 to 98, further comprising applying one or more geometric calibration parameters to at least some of the 2D images before generating the 3D reconstruction. [0407] 100. The method of any one of Examples 84 to 99, wherein generating the 3D reconstruction is based on pose data previously acquired using the imaging arm. [0408] 101. A method for imaging an anatomic region, the method comprising: [0409] receiving, from a detector carried by an imaging arm of an x-ray imaging apparatus, a plurality of 2D images of an anatomic region, wherein the 2D images are obtained during manual rotation of the imaging arm, and wherein the imaging arm is coupled to a shim structure during the manual rotation; [0410] receiving pose data of the imaging arm during the manual rotation; and [0411] generating, based on

the 2D images and the pose data, a 3D representation of the anatomic region. [0412] 102. The method of Example 101, wherein the x-ray imaging apparatus is a mobile C-arm apparatus. [0413] 103. The method of Example 101 or Example 102, wherein the manual rotation comprises a propeller rotation of at least 180 degrees. [0414] 104. The method of any one of Examples 101 to 103, wherein the shim structure inhibits orbital rotation of the imaging arm. [0415] 105. The method of any one of Examples 101 to 104, wherein the x-ray imaging apparatus comprises a support arm coupled to the imaging arm, and the shim structure is configured to inhibit movement of the imaging arm relative to the support arm. [0416] 106. The method of Example 105, wherein the shim structure is configured to fill at least one gap in an interface between the support arm and the imaging arm. [0417] 107. The method of Example 106, wherein the shim structure comprises at least one elongate member configured to be positioned within the at least one gap. [0418] 108. The method of any one of Examples 101 to 107, wherein the pose data is received from at least one sensor associated with the x-ray imaging apparatus, and wherein the at least one sensor comprises a motion sensor coupled to the imaging arm. [0419] 109. The method of any one of Examples 101 to 108, further comprising temporally synchronizing the 2D images to the pose data. [0420] 110. The method of any one of Examples 101 to 109, wherein temporally synchronizing the 2D images to the pose data comprises identifying a pose of the imaging arm at a time when each 2D image was obtained. [0421] 111. The method of Example 110, wherein the pose comprises a rotation angle of the imaging arm. [0422] 112. The method of any one of Examples 101 to 111, wherein the pose data is second pose data and generating the 3D reconstruction is based on first pose data previously acquired using the imaging arm. [0423] 113. A method for imaging an anatomic region, the method comprising: [0424] receiving, from a detector carried by an imaging arm of a mobile C-arm apparatus, a plurality of 2D projection images of the anatomic region, wherein the 2D projection images are obtained during manual rotation of the imaging arm, and wherein the imaging arm is mechanically stabilized by a shim structure during the manual rotation; [0425] determining a plurality of rotation angles of the imaging arm during the manual rotation, wherein each rotation angle is associated with a corresponding 2D projection image; [0426] generating, based on the 2D projection images and the associated rotation angles, a 3D reconstruction of the anatomic region; and [0427] outputting the 3D reconstruction on a graphical user interface configured to provide guidance during a medical procedure performed in the anatomic region.

CONCLUSION

[0428] Although many of the embodiments are described above with respect to systems, devices, and methods for performing a medical procedure in a patient's lungs, the technology is applicable to other applications and/or other approaches, such as medical procedures performed in other anatomic regions (e.g., the musculoskeletal system). Moreover, other embodiments in addition to those described herein are within the scope of the technology. Additionally, several other embodiments of the technology can have different configurations, components, or procedures than those described herein. A person of ordinary skill in the art, therefore, will accordingly understand that the technology can have other embodiments with additional elements, or the technology can have other embodiments without several of the features shown and described above with reference to FIGS. **1**A-**27**C.

[0429] The various processes described herein can be partially or fully implemented using program code including instructions executable by one or more processors of a computing system for implementing specific logical functions or steps in the process. The program code can be stored on any type of computer-readable medium, such as a storage device including a disk or hard drive. Computer-readable media containing code, or portions of code, can include any appropriate media known in the art, such as non-transitory computer-readable storage media. Computer-readable media can include volatile and non-volatile, removable and non-removable media implemented in any method or technology for storage and/or transmission of information, including, but not limited to, random-access memory (RAM), read-only memory (ROM), electrically erasable programmable

read-only memory (EEPROM), flash memory, or other memory technology; compact disc read-only memory (CD-ROM), digital video disc (DVD), or other optical storage; magnetic cassettes, magnetic tape, magnetic disk storage, or other magnetic storage devices; solid state drives (SSD) or other solid state storage devices; or any other medium which can be used to store the desired information and which can be accessed by a system device.

[0430] The descriptions of embodiments of the technology are not intended to be exhaustive or to limit the technology to the precise form disclosed above. Where the context permits, singular or plural terms may also include the plural or singular term, respectively. Although specific embodiments of, and examples for, the technology are described above for illustrative purposes, various equivalent modifications are possible within the scope of the technology, as those skilled in the relevant art will recognize. For example, while steps are presented in a given order, alternative embodiments may perform steps in a different order. The various embodiments described herein may also be combined to provide further embodiments.

[0431] As used herein, the terms "generally," "substantially," "about," and similar terms are used as terms of approximation and not as terms of degree, and are intended to account for the inherent variations in measured or calculated values that would be recognized by those of ordinary skill in the art.

[0432] Moreover, unless the word "or" is expressly limited to mean only a single item exclusive from the other items in reference to a list of two or more items, then the use of "or" in such a list is to be interpreted as including (a) any single item in the list, (b) all of the items in the list, or (c) any combination of the items in the list. Additionally, the term "comprising" is used throughout to mean including at least the recited feature(s) such that any greater number of the same feature and/or additional types of other features are not precluded. As used herein, the phrase "and/or" as in "A and/or B" refers to A alone, B alone, and A and B.

[0433] To the extent any materials incorporated herein by reference conflict with the present disclosure, the present disclosure controls.

[0434] It will also be appreciated that specific embodiments have been described herein for purposes of illustration, but that various modifications may be made without deviating from the technology. Further, while advantages associated with certain embodiments of the technology have been described in the context of those embodiments, other embodiments may also exhibit such advantages, and not all embodiments need necessarily exhibit such advantages to fall within the scope of the technology. Accordingly, the disclosure and associated technology can encompass other embodiments not expressly shown or described herein.

Claims

1. (canceled)

2. A method comprising: performing a first manual rotation of an imaging arm of an x-ray imaging apparatus; obtaining, using a detector carried by the imaging arm, a plurality of first images of a set of fiducial markers during the first manual rotation; obtaining, using a motion sensor coupled to the imaging arm, first pose data of the imaging arm during the first manual rotation; determining, using one or more processors, a set of calibration parameters for the x-ray imaging apparatus based on the first images and the first pose data; performing a second manual rotation of the imaging arm of the x-ray imaging apparatus; obtaining, using the detector, a plurality of second images of an anatomic region of a patient during the second manual rotation; obtaining, using the motion sensor, second pose data of the imaging arm during the second manual rotation; and generating, using the one or more processors, a 3D representation of the anatomic region based on the second images, the second pose data, and the calibration parameters.

3. The method of claim 2, wherein the x-ray imaging apparatus is a mobile C-arm apparatus.

4. The method of claim 2, wherein the imaging arm is not motorized.

5. The method of claim 2, wherein the first manual rotation and the second manual rotation each comprise a propeller rotation of the imaging arm.

6. The method of claim 2, wherein the first manual rotation and the second manual rotation each comprise an orbital rotation of the imaging arm.

7. The method of claim 2, wherein the first manual rotation and the second manual rotation each comprise a rotation of at least 100°.

8. The method of claim 2, wherein the motion sensor comprises an accelerometer, a gyroscope, an inertial measurement unit, or a combination thereof.

9. The method of claim 2, wherein the detector comprises a flat panel detector.

10. The method of claim 2, wherein the detector comprises an image intensifier.

11. The method of claim 2, wherein the set of calibration parameters comprises geometric calibration parameters, distortion correction parameters, or a combination thereof.

12. The method of claim 2, wherein the set of calibration parameters comprises a lookup table storing a plurality of angles of the imaging arm and one or more calibration parameters for each angle.

13. The method of claim 12, wherein generating the 3D representation comprises, for each second image of the plurality of the second images: determining a target angle of the imaging arm at a time the second image was obtained based on the second pose data, retrieving, from the lookup table, one or more calibration parameters for an angle corresponding to the target angle of the imaging arm, and adjusting the second image using the retrieved one or more calibration parameters.

14. The method of claim 2, wherein the 3D representation is generated without using a fiducial marker board positioned near the patient.

15. The method of claim 2, wherein the 3D representation comprises a cone-beam computed tomography reconstruction.

16. The method of claim 2, further comprising performing an alignment process before performing the second manual rotation.

17. The method of claim 16, wherein the alignment process comprises: obtaining, using the detector, one or more test images of the anatomic region, and identifying, using the one or more processors, image locations in the one or more test images that would be visible in a 3D representation generated from the one or more test images.

18. The method of claim 17, wherein the alignment process comprises outputting, on a display, the one or more test images together with an indicator representing the image locations that would be visible in the 3D representation generated from the one or more test images.

19. The method of claim 2, wherein the anatomic region is part of a lung of the patient.

20. The method of claim 2, wherein the anatomic region is part of a musculoskeletal system of the patient.

21. The method of claim 2, wherein the imaging arm is stabilized during the first manual rotation and the second manual rotation.

22. A method comprising: performing a first manual rotation of an imaging arm of an x-ray imaging apparatus; obtaining, using a detector carried by the imaging arm, a plurality of first images of a set of fiducial markers during the first manual rotation; obtaining first data indicative of a plurality of first poses of the imaging arm during the first manual rotation; determining, using one or more processors, a set of calibration parameters for the x-ray imaging apparatus based on the first images and the first data; performing a second manual rotation of the imaging arm of the x-ray imaging apparatus; obtaining, using the detector, a plurality of second images of an anatomic region of a patient during the second manual rotation; obtaining second data indicative of a plurality of second poses of the imaging arm during the second manual rotation; and generating, using the one or more processors, a 3D representation of the anatomic region based on the second images, the second data, and the calibration parameters.

23. The method of claim 22, wherein the x-ray imaging apparatus is a mobile C-arm apparatus.

24. The method of claim 22, wherein the first manual rotation and the second manual rotation each comprise a propeller rotation or an orbital rotation of the imaging arm.

25. The method of claim 22, wherein the first manual rotation and the second manual rotation each comprise a rotation of at least 100°.

26. The method of claim 22, wherein the first data and the second data are obtained using a motion sensor coupled to the imaging arm.

27. The method of claim 22, wherein the first data and the second data are obtained using an imaging device that is configured to image one or more fiducial markers on the imaging arm.

28. The method of claim 22, wherein the set of calibration parameters comprises geometric calibration parameters, distortion correction parameters, or a combination thereof.

29. The method of claim 22, wherein the set of calibration parameters comprises a lookup table storing a plurality of angles of the imaging arm and one or more calibration parameters for each angle.

30. The method of claim 29, wherein generating the 3D representation comprises, for each second image of the plurality of the second images: determining a target angle of the imaging arm at a time the second image was obtained based on the second data, retrieving, from the lookup table, one or more calibration parameters for an angle corresponding to the target angle of the imaging arm, and adjusting the second image using the retrieved one or more calibration parameters.

31. The method of claim 22, wherein the 3D representation comprises a cone-beam computed tomography reconstruction.