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Repeatable Ultrasound

Abstract

Systems and methods for repeatable ultrasound are disclosed. These systems and methods enable generation of consistent ultrasound images across serial ultrasound examinations, which are suitable for the early detection and management of one or more medical conditions, including rheumatoid arthritis. These systems can include a robotic manipulator that holds and operates an ultrasound scanner for scanning a patient's anatomy. Additionally, sensors are used to detect position and orientation of the patient anatomy to enable the robotic manipulator to consistently hold and orient the ultrasound scanner based on the position and orientation of the patient anatomy during an ultrasound examination. In aspects, an anatomy fixture can be generated to support the patient anatomy in the same position and orientation across the serial ultrasound examinations.

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Background/Summary

BACKGROUND

[0001] Ultrasound systems can generate ultrasound images by transmitting sound waves at frequencies above the audible spectrum into a body, receiving echo signals caused by the sound waves reflecting from internal body parts, and converting the echo signals into electrical signals for image generation. Because they are non-invasive and non-ionizing, ultrasound systems are used ubiquitously. One example where ultrasound systems are used is rheumatology.

[0002] Rheumatology treats auto-immune disorders that attack a patient's joint lining, including rheumatoid arthritis that is common in hands and feet. If not detected early, rheumatoid arthritis can erode and permanently damage the patient's joint, and even progress to the bone. Some imaging techniques other than ultrasound can be used, such as X-ray and magnetic resonance imaging (MRI); however, X-ray is poor at detecting erosion caused by rheumatoid arthritis and therefore poor at early detection, and MRI is often not accessible, or is too expensive, for many patients. Hence, detection and monitoring of rheumatoid arthritis via ultrasound is common.

[0003] Treatment of rheumatoid arthritis usually includes serial ultrasound scanning over multiple examinations that occur periodically, e.g., every three months. For proper assessment of the progression of rheumatoid arthritis, it is imperative that the images generated during these multiple examinations have essentially identical views. However, operator dependency (among different examinations and/or different operators) can prevent the level of reproducibility needed to generate matching image views. Moreover, the weight of a gel pad used in some ultrasound examinations is often large enough to cause compression of the synovium or swollen joint lining, skewing imaging results.

[0004] Hence, many ultrasound operators often use a coupling gel instead of a gel pad. However, floating the ultrasound scanner in the gel at a constant height above the patient and without touching the patient requires extensive training and experience, and is simply not achievable for most ultrasound operators. This deficiency can prevent the generation of matching image views needed in the serial ultrasound examinations.

[0005] In some cases, a water bath is used in lieu of gel pads and coupling gel. However, the ultrasound operator is required to consistently float the scanner in the water relative to the patient anatomy. Similar to the use of coupling gel, this is simply not achievable for most ultrasound operators who usually tilt the scanner, resulting in inconsistent and unusable imaging results. Further, the motion of the water in the water bath (e.g., introduced by the movement of the scanner, such as when an operator does not smoothly move the scanner) can introduce noise artifacts for some imaging modes, such as color Doppler. Moreover, many ultrasound scanners are simply not approved for submersion in water.

[0006] Accordingly, conventional ultrasound systems may not be suitable for the assessment of certain medical conditions, such as rheumatoid arthritis, and the use of these conventional ultrasound systems can result in poor patient care, including permanent joint damage. In some examples, the poor patient care includes prolonged use of chemotherapy drugs during treatment that could be reduced or eliminated if the medical condition (e.g., rheumatoid arthritis) were detected and treated early.

SUMMARY

[0007] Systems and methods for repeatable ultrasound are disclosed. These systems and methods enable generation of consistent ultrasound images across serial ultrasound examinations, which are suitable for the early detection and management of certain medical conditions, including rheumatoid arthritis. These systems can include a robotic manipulator that holds and operates an ultrasound scanner for scanning a patient anatomy. Additionally, sensors can be used to detect

position and orientation of the patient anatomy to enable the robotic manipulator to consistently hold and orient the ultrasound scanner based on the position and orientation of the patient anatomy during an ultrasound examination. In aspects, an anatomy fixture can be generated to support the patient anatomy in the same position and orientation across the serial ultrasound examinations.

[0008] In some aspects, an ultrasound system is disclosed. The ultrasound system includes an ultrasound scanner, a robotic manipulator, a processor system, an adaptive-registration system, and a database. The ultrasound scanner is configured to generate ultrasound data based on received reflections of ultrasound signals transmitted by the ultrasound scanner at a patient anatomy. The robotic manipulator is configured to couple to the ultrasound scanner, the robotic manipulator configured to control positioning, movement, and operation of the ultrasound scanner. The processor system is configured to generate scan instructions for the robotic manipulator and receive the ultrasound data from the ultrasound scanner. The adaptive-registration system is configured to determine a position and orientation of the patient anatomy and adjust the robotic manipulator to orient the ultrasound scanner based on the determined position and orientation of the patient anatomy. The database is configured to store data corresponding to the ultrasound data and anatomy-registration data associated with the determined position and orientation of the patient anatomy.

[0009] In some aspects, a method for repeatable ultrasound is disclosed. The method includes providing a vessel having an interior volume, detecting exterior boundaries of a patient anatomy located within the interior volume of the vessel, and detecting a spatial relation of the patient anatomy relative to the vessel. The method also includes generating anatomy-registration data corresponding to the patient anatomy based on the spatial relation of the patient anatomy relative to the vessel and the exterior boundaries of the patient anatomy. Further, the method includes determining movement instructions for a robotic manipulator based on the anatomy-registration data and providing the movement instructions to the robotic manipulator to move and operate an ultrasound scanner for scanning the patient anatomy.

Description

BRIEF DESCRIPTION OF THE DRAWINGS

[0010] The appended drawings illustrate examples and are, therefore, exemplary embodiments and not considered to be limiting in scope. Throughout the drawings, the same numbers are used to reference like features and components.

[0011] FIG. **1** illustrates an ultrasound system for generating consistent ultrasound images suitable for the early detection and management of one or more medical conditions.

[0012] FIG. **2** illustrates an adaptive-registration system for generating consistent ultrasound images suitable for the early detection and management of one or more medical conditions.

[0013] FIG. **3** illustrates an example implementation of an anatomy-capture device as part of the fixture generator from FIG. **1**.

[0014] FIG. **4** illustrates an implementation of an example scanner holder, which is part of the ultrasound system from FIG. **1**.

[0015] FIG. **5** illustrates an example implementation of another scanner holder, which is part of the ultrasound system from FIG. **1**.

[0016] FIG. **6** illustrates an example implementation of another scanner holder, which is part of the ultrasound system from FIG. **1**.

[0017] FIG. **7** illustrates an example implementation of a user interface, which is part of the ultrasound system **100** of FIG. **1**.

[0018] FIG. **8** depicts a method for repeatable ultrasound, in accordance with one or more implementations.

[0019] FIG. **9** depicts a method for repeatable ultrasound, in accordance with one or more implementations.
[0020] FIG. **10** depicts a method for repeatable ultrasound, in accordance with one or more implementations.
[0021] FIG. **11** depicts a method for generating an anatomy fixture for repeatable ultrasound, in accordance with one or more implementations.
[0022] FIG. **12** represents an example machine-learning architecture used to train a machine-learned model M, which can be used to implement at least some of the techniques disclosed herein.
[0023] FIG. **13** represents an example model using a Convolutional Neural Network (CNN) to process an input image, which includes representations of objects that can be identified via object recognition.
[0024] FIG. **14** illustrates a block diagram of an example computing device that can perform one or more of the operations described herein, in accordance with some implementations.

DETAILED DESCRIPTION

[0025] Disclosed herein are systems and methods for repeatable ultrasound. Conventional ultrasound systems may not be suitable for the assessment of some medical conditions, such as rheumatoid arthritis, and the use of such conventional ultrasound systems can result in poor patient care, leading to permanent joint damage. In some examples, the poor patient care includes the prolonged use of chemotherapy drugs during treatment that could be reduced or eliminated if the rheumatoid arthritis could be detected and treated early.
[0026] Accordingly, systems, devices, and techniques are disclosed herein for generating consistent ultrasound images suitable for the early detection and management of one or more medical conditions. An ultrasound system in accordance with the present invention includes a vessel that can contain a coupling agent, such as water or gel. The ultrasound system includes a robotic manipulator, which is a reprogrammable and multifunctional mechanical device capable of moving objects or tools through programmed motions to perform various tasks. The robotic manipulator can be, for example, a robotic arm or multi-axis mill, which can hold and consistently orient an ultrasound scanner or can include one or more dedicated and/or integrated acoustic ultrasound arrays. The ultrasound system includes an ultrasound scanner holder that can hold multiple ultrasound scanners, each of which can be retrieved by the robotic manipulator.
[0027] The ultrasound system also includes a registration system, such as an adaptive-registration system, which determines a position and orientation of a patient anatomy before, during, and after an ultrasound examination and adjusts the robotic manipulator to orient the scanner based on the position and orientation of the patient anatomy during the ultrasound examination. In embodiments, the adaptive-registration system includes electronic sensors to determine the position and orientation of the patient anatomy. Additionally or alternatively, the adaptive-registration system can include a mechanical anatomy fixture used to determine the position and orientation of the patient anatomy. Hence, the ultrasound system reduces and/or removes the dependency of the operator and inconsistencies resulting from patient movement, so that the ultrasound system can generate matching image views needed in serial ultrasound examinations for the assessment and treatment of a medical condition such as rheumatoid arthritis.
[0028] Using the techniques described herein facilitates remote and in-person examinations, supports both procedural and diagnostic purposes, and enables the use of interchangeable scanners that can consistently and repeatedly follow the same path and generate matching image views even when different scanners or transducers are used. Also, these techniques can be operator independent and can be implemented via a mobile ultrasound system or a fixed ultrasound system. Accordingly, the disclosed techniques enhance the user experience and can provide more accurate ultrasound data for serial examinations, in comparison to conventional ultrasound systems.

Example Ultrasound System

[0029] FIG. **1** illustrates an ultrasound system **100** for generating consistent ultrasound images suitable for the early detection and management of one or more medical conditions. The ultrasound system **100** includes a vessel **102**, a fixture generator **104** that can include an anatomy-capture device **106**, a position controller **108**, a processor system **110**, a robotic manipulator **112**, and a scanner holder **114** that can hold multiple ultrasound scanners **116**, also referred to as ultrasound probes and/or ultrasound transducers. In some aspects, the scanner holder **114** can hold multiple transducer arrays or scan heads that are interchangeable with a single scanner body.

[0030] The vessel **102** can include any suitable container that can hold a coupling agent **118**, such as water or gel, which conforms to a patient anatomy **120** (e.g., hand **120-1**) and enables the patient anatomy **120** to be inserted into the vessel **102** for scanning via a selected ultrasound scanner **116-1**. Although the examples described herein relate to a human such as a human hand, the patient anatomy **120** can be any tissue or anatomy that can be penetrated by ultrasound, including that of animals, plants, insects, etc. The scanning includes transmitting and receiving ultrasound signals **122**. The coupling agent **118** acts as a conductor that facilitates the transmission of the ultrasound signals **122** between the ultrasound scanner **116** and the patient anatomy **120**. In aspects, the coupling agent **118** includes a medication, such as a pain medication. For instance, the patient anatomy **120** can be injured and have foreign objects embedded in their anatomy, such as glass shards or plastic shrapnel. In an example, the coupling agent **118** includes a gas, such as a dense or foggy gas for coupling the ultrasound scanner **116-1** to the patient anatomy **120** to provide a medium for conducting the ultrasound signals **122**. In some aspects, the ultrasound system **100** applies the coupling agent **118** during the examination, such as with a nozzle attached to the robotic manipulator **112**. The nozzle can dispense the coupling agent **118** to the patient's skin as the scanner **116-1** is moved along the patient to image the patient anatomy **120**.

[0031] The robotic manipulator **112** can be implemented to hold and control one or more interventional instruments to enable the ultrasound system **100** to be used for both diagnostic and procedural purposes. The robotic manipulator **112** is a robotic mechanism or device, such as an automated machine, which has joints and rigid links and is programmable to move in multiple degrees of freedom (e.g., six degrees of freedom). In an example, a user can select a point of an ultrasound image displayed on a display of the ultrasound system **100** and the ultrasound system **100** automatically inserts an interventional instrument (e.g., needle) to guide the tip to the user-selected point. Moreover, the ultrasound system **100** can be operated by a remote user, supporting remote assessment and procedures as well as telemedicine. In some embodiments, the ultrasound system **100** is portable. A portable ultrasound system can, for example, be configured in a way that it fits in a hand-carried bag, and/or can be assembled and placed on a desk-top, table, or medical cart. In other embodiments, the ultrasound system is fixed (e.g., stationary system in a care facility, such as a rack-mounted ultrasound system).

[0032] Examples of the patient anatomy **120** are not limited to hands and/or feet and can include any anatomy that generally is scanned using a stringent protocol that requires repeatable imaging. Hence, the patient anatomy **120** can include elbows, knees, wrists, ankles, shoulders, etc. For instance, assessment and treatment of a rotator-cuff injury requires consistent scans across multiple ultrasound examinations, similar to that needed for the assessment and treatment of rheumatoid arthritis. Further, the patient anatomy **120** can include areas of the body that have synovial tissue, such as tendons, joint capsules, and joint membranes. The patient anatomy **120** can also include other types of tissue than synovial tissue, such as muscles. For instance, detection and treatment of atrophy requires multiple studies repeated every few months, and consistent imaging results. The patient anatomy **120** can also include skin, for the tracking of skin lesions, such as skin cancers, which can require repeatable scans over multiple examinations. Accordingly, the techniques disclosed herein are not limited to detecting and managing rheumatoid arthritis; this disease is described throughout the specification for exemplary purposes and is not meant to be limiting.

[0033] To accommodate these various patient anatomies, the vessel **102** can be of any suitable shape and size. In an example, the vessel **102** includes a bucket or open container. In another example, the vessel **102** includes a bladder. The bladder can be of sufficient size so that the patient anatomy **120** fits inside the vessel **102**. In an example, the vessel **102** includes a tank in which the patient can fit inside (e.g., by laying down, sitting, or standing). In aspects, the vessel **102** includes a port on a portion of the vessel **102** (not shown in FIG. **1** for clarity), such as on the side of the vessel **102**. The port can facilitate insertion of the patient anatomy **120** into the vessel **102** and prevent the coupling agent from leaking out of the vessel **102**.

[0034] The fixture generator **104** receives the patient anatomy **120** (illustrated in FIG. **1** as hand **120-1**) and generates an anatomy fixture **124** from the patient anatomy **120**. The anatomy fixture **124** can subsequently support the patient anatomy **120** in the vessel **102** during an ultrasound examination. In aspects, the fixture generator **104** includes an anatomy-capture device **106** that captures (e.g., senses, detects, measures, etc.) various characteristics of the patient anatomy **120**, such as shape, size, orientation, etc., in a three-dimensional coordinate system (or a four-dimensional (4D) coordinate system including a time element). The fixture generator **104** can then generate the anatomy fixture **124** from the characteristics of the patient anatomy **120** determined by the anatomy-capture device **106**. In an example, the anatomy-capture device **106** generates the negative, or inverse, of the patient anatomy **120** as the shape. For instance, the anatomy-capture device **106** can generate a mold of the patient anatomy **120**, where the mold includes an imprint (e.g., an impression defining a negative copy of the patient anatomy **120**) usable to reproduce an outline of the patient anatomy **120**. The mold can be created in any suitable way, some examples of which are described in detail below. In some cases, the anatomy-capture device **106** generates a three-dimensional (3D) computer model of the patient anatomy **120** based on sensor data from sensors (e.g., optical sensors, infrared sensors, LIDAR sensors, RF sensors, etc.) used to sense the characteristics and features of the patient anatomy **120**. Then, the fixture generator **104** can generate a physical mold from the 3D computer model. Additionally or alternatively, the fixture generator **104** can generate the anatomy fixture **124** from the 3D computer model.

[0035] The anatomy fixture **124** can include the mold. The mold can subsequently receive the patient anatomy into the impression to cause the patient anatomy to be positioned in substantially the same orientation that it had when the anatomy-capture device **106** captured the characteristics of the patient anatomy **120** and created the mold. In some aspects, the fixture generator **104** includes a 3D printer that can 3D-print the anatomy fixture **124**. In other aspects, at least a portion of the coupling agent **118** can be solidified, using the robotic manipulator **112** or an external energy source, to form the mold around the patient anatomy **120** for subsequent removal.

[0036] Alternatively or additionally, the fixture generator **104** can include a shape-adapting material (e.g., metamaterial, memory-shaping material) or mechanism that can be shaped and reshaped to generate the anatomy fixture **124**. The anatomy fixture **124** and/or the vessel **102** can be part of an adaptive-registration system that generates position and orientation data of the patient anatomy **120** during an ultrasound examination, as illustrated in more detail in FIGS. **2** and **3**.

[0037] FIG. **2** illustrates an adaptive-registration system **200** for generating consistent ultrasound images suitable for the early detection and management of one or more medical conditions. The adaptive-registration system **200** includes a vessel **202**, which is an example of the vessel **102** in FIG. **1**. The adaptive-registration system **200** also includes one or more patient-worn components (e.g., patient-worn components **204**, **206**, and **208**), which can include sensors and/or actuators that are in communication with actuators and/or sensors **210** coupled or affixed to the vessel **202**. The communication between the patient-worn components **204**, **206**, and **208** and the actuators and/or sensors **210** can include a wireless communication link, such as a near-field communication (NFC) link. For clarity, the communication is illustrated in FIG. **2** only for the patient-worn component **204**; however, the communication can be with any combination of the patient-worn components **204**, **206**, and **208** and the actuators and/or sensors **210**. As the patient moves the patient anatomy **120** inside the vessel **202** during an ultrasound examination, the ultrasound system **100** can determine anatomy-registration data that denotes a spatial relation (e.g., position and orientation) of the patient anatomy **120** with respect to the vessel **202** based on the respective positions of the patient-worn components **204**, **206**, and **208** as detected by the actuators and/or sensors **210**. Any suitable positioning algorithm can be used, including triangulation in a Cartesian coordinate system, for example, to determine the spatial relation of the patient-worn components **204**, **206**, and **208** relative to the actuators and/or sensors **210**. The patient-worn component **204** is illustrated as a ring. The patient-worn component **206** is illustrated as a wrist band. The patient-worn component **208** is illustrated as a patch affixed to the palm of the patient's hand or to a glove worn by the patient's hand. The patient-worn components **204**, **206**, and **208** are exemplary and not meant to be limiting. Further, the system can include any suitable number of patient-worn components.

[0038] FIG. **3** illustrates an example implementation **300** of an anatomy-capture device **302** as part of the fixture generator **104** from FIG. **1**. The anatomy-capture device **302** can be an implementation of or a component of the anatomy-capture device **106**. The anatomy-capture device **302** includes an array of pins **304** that form an impression of a patient anatomy **306** (e.g., patient anatomy **120**) when the patient anatomy **306** is pressed against the anatomy-capture device **302**. The pins **304** each have a central axis and are each displaceable along their central axis. The pins **304** of the anatomy-capture device **302** can be spring loaded, so that when the patient anatomy **306** is removed from the anatomy-capture device **302**, the pins **304** return to their default, upright position. The ultrasound system **100** can use sensors (e.g., a sensor on each pin **304**) to detect the depth and location of each of the pins **304** as anatomy-registration data that represents the contour of the exterior surface of a portion of the patient anatomy **306** that contacted the pins **304**, such as a lower half of the patient anatomy **306**. The anatomy-registration data provides a position and orientation of the patient anatomy **306** with respect to the anatomy-capture device **302** and/or the vessel **202**. For instance, the anatomy-capture device **302** can be anchored to the vessel **202** at a known position and orientation to define a fixed spatial relation between the anatomy-capture device **302** and the vessel **202**.

[0039] In an example, settings (e.g., depth, location, etc.) of the array of pins **304** is recorded and used as an initialization setting for a subsequent examination. For instance, the array of pins **304** can be set during a subsequent examination based on the registration data determined during a current examination. Further, the settings can be used to establish boundaries of the patient anatomy **306** (e.g., location of exterior surfaces of the patient anatomy **306**, size of hand, etc.), to prevent the ultrasound system from causing the ultrasound scanner to collide with the patient anatomy **306**. In embodiments, the ultrasound system uses the array of pins **304** as a temporary fixture to generate the anatomy fixture **124** (shown in FIG. **1**). For instance, the ultrasound system can include a 3D printer that prints the anatomy fixture **124** based on the settings of the array of pins **304**. Additionally or alternatively, the ultrasound system can generate a prosthetic for the patient, or a cast (e.g., if the patient has an injury), with the 3D printer based on the settings of the array of pins **304**.

[0040] In some implementations, the fixture generator **104** can use the anatomy-capture device **302** as the anatomy fixture **124** for subsequent ultrasound examinations. For example, the anatomy-capture device **302** can include one or more actuators (e.g., linear actuators, electromagnets, etc.) that can displace the pins **304** to move the pins **304** to their respective depth according to the initialization setting. The one or more actuators can displace at least a subset of the pins in the array of pins. Each pin **304** can be manipulated by a different actuator. Alternatively, a single actuator can move and position multiple pins **304**. In an example, on a subsequent examination, the actuators can position the pins **304** to match the recorded settings of the array of pins **304**. Then, the patient can place their anatomy into the impression created by the array of pins **304**, which matches the position and orientation of the patient anatomy **306** from their previous examination (e.g., initial examination). In this way, the anatomy-capture device **302** becomes or acts as the anatomy fixture **124**. Such an implementation can reduce the amount of materials and time needed to produce (e.g., 3D print) the anatomy fixture **124** because the actuators and the pins **304** enable the anatomy-capture device **302** to precisely recreate the same impression for the patient anatomy **306** each examination without additional materials. Such actuators and pins also enable the anatomy-capture device **302**, acting as the anatomy fixture **124**, to be dynamically adaptable to different patients.

[0041] Returning to FIG. **1**, the fixture generator **104** provides anatomy-registration data **126** to the position controller **108**. The anatomy-registration data **126** can include data generated by electrical and/or mechanical means, as described above with respect to FIGS. **2** and **3**. The position controller **108** can also receive registration data **128** from the processor system **110**. This registration data **128** can be image-based registration data **128-1** (e.g., determined based on ultrasound-image data generated by the ultrasound system **100**). For instance, the processor system **110** can implement a machine-learned model that receives image data generated as part of a current ultrasound examination, as well as image data from a database **130** that maintains images **132** and/or ultrasound data (e.g., relative position and orientation of a patient anatomy) from previous ultrasound examinations. The machine-learned model can generate the image-based registration data **128-1** by processing the current and previous ultrasound-image data. The image-based registration data **128-1** can include dimensions in a coordinate system and/or angular dimensions that define movements for the robotic manipulator **112** and/or the scanner **116** to enable a current ultrasound image to have a matching view to a previous ultrasound image.

[0042] Additionally or alternatively, the registration data **128** from the processor system **110** can include sensor-based registration data **128-2**. For example, the ultrasound system **100** can include a source and/or sensor **134** configured to scan the patient anatomy **120** while the patient anatomy is located in the vessel **102** to determine the position and/or orientation of the patient anatomy **120**. The source and/or sensor **134** can be attached to the robotic manipulator **112**, to enable movements of the source and/or sensor **134** to be fixed relative to the selected scanner **116-1**. The source and/or sensor **134** can be based on light (e.g., a laser, light detection and ranging (LIDAR), etc.), radar, sonar, optical, non-visible spectrum electromagnetic (EM) radiation, and the like. In an example, the source and/or sensor **134** is implemented in the selected scanner **116-1** and uses ultrasound to generate the sensor-based registration data **128-2**. In embodiments, the source and/or sensor **134** can include a line scanner. In embodiments, registration includes affixing a fiducial marker to the patient's skin, which can be detected via the source and/or sensor **134**, such as a line scanner. A fiducial marker can include a coating, a grid, a tattoo, one or more marker dots, etc.

[0043] Additionally or alternatively to the source and/or sensor **134**, the ultrasound system **100** can generate a scout image (e.g., a superficial or preliminary scan) to determine boundaries of the patient anatomy **120**, which reduces the risk of causing the scanner **116-1** to collide with the patient anatomy **120**. Further, the scout image can also be useful because the desired anatomy does not always follow the profile of the patient's skin, like an internal bone. Hence, it may be desirable to position and move the scanner **116** to follow the internal bone, not the skin, for proper imaging, while still avoiding a collision between the scanner **116** and the patient's skin.

[0044] In an example, the ultrasound system **100** generates an interventional instrument based on the registration data **128** and/or the ultrasound-image data to precisely fit the patient anatomy **120**. For example, the ultrasound system **100** can use the registration data **128** and/or the ultrasound-image data to generate (e.g., 3D print) a curved needle that uniquely fits the patient anatomy **120** for a specific procedure. The needle can be printed with markers that are detectable via ultrasound, to help guide insertion of the needle during a procedure. Because the needle can be specifically generated based on the registration data so that it can be inserted in a specific way/trajectory to a specific patient anatomy, the markers printed on the needle can be placed at locations that the system determines are most likely to be detected via the ultrasound. The system can omit to print markers on locations of the needle that the system determines are not likely to be detected by the ultrasound. Hence, the system can generate the needle for a specific application for a specific patient, during an examination, rather than use a conventional needle, thus providing better needle-insertion guidance compared to use of a conventional needle.

[0045] The position controller **108** generates movement instructions **136** based on the registration data **128** from the processor system **110** and/or the anatomy-registration data **126** from the fixture generator **104** and/or the adaptive-registration system **200**. The movement instructions **136** direct movement and operation of the robotic manipulator **112** to enable the selected scanner **116-1** to generate scan data **138** (e.g., ultrasound data) so that a current ultrasound image has a matching view to a previous ultrasound image (e.g., from a previous ultrasound examination). In aspects, the position controller **108** can use the registration data **128** and/or the anatomy-registration data **126** to determine boundaries of the patient anatomy **120** and generate the movement instructions **136** to prevent the robotic manipulator **112** from forcing the scanner **116** to collide with the patient anatomy **120**.

[0046] The position controller **108** can also provide scanner-configuration data **140** to the processor system **110**. The scanner-configuration data **140** can indicate position data for the scanner **116-1**. For example, at various positions according to the scanner-configuration data **140**, the scanner **116-1** can be enabled to transmit and receive ultrasound in a first configuration, and at various positions according to the scanner-configuration data **140**, the scanner **116-1** can be enabled to transmit and receive ultrasound in a second configuration. The configurations can include any suitable data, such as a frequency, bandwidth, imaging mode, array selection, etc., for configuring the scanner **116-1**. The processor system **110** receives the scanner-configuration data **140** from the position controller **108** and provides scan instructions **142** to the scanner **116-1**. The processor system **110** also receives the scan data **138** (e.g., ultrasound imaging data) from the scanner **116**.

[0047] The robotic manipulator **112** retrieves the scanner **116-1** from the scanner holder **114** and holds the scanner **116-1**. The robotic manipulator **112** can hold the scanner **116-1** in numerous ways, some examples of which include using a biasing force to grip the scanner **116-1**, a magnetic coupling, a threaded coupling, a snap-fit coupling, etc. In aspects, the robotic manipulator **112** is communicably coupled to the ultrasound scanner **116-1** such that the robotic manipulator **112** can pass instructions to the scanner **116-1** from the processor system **110**. In some implementations, the robotic manipulator **112** provides power to the scanner **116-1**, eliminating the need for the scanner **116-1** to use a battery or an independent power source. Providing power in this way can significantly reduce the heat generated by the scanner **116-1**, providing better patient comfort and longer scan times with shorter dead times between scanning, compared to conventional ultrasound systems. The scan instructions **142** from the processor system **110** can be transferred through the robotic manipulator **112** to the scanner **116-1**. Hence, the connection between the robotic manipulator **112** and the scanner **116-1** can include not only power but also data. Such a connection can also transfer the scan data **138** generated by the scanner **116-1** to the processor system **110**. The scanner holder **114** can include any suitable device for holding, storing, and orienting the one or more scanners **116**, as described in further detail in FIGS. **4-6**.

[0048] FIG. **4** illustrates an implementation **400** of an example scanner holder **402**, which is part of the ultrasound system from FIG. **1**. The scanner holder **402** is an example of the scanner holder **114** in FIG. **1**. Also illustrated in FIG. **4** is a robotic arm **404**, which is an example of the robotic manipulator **112** in FIG. **1**. The robotic arm **404** is just one example of the robotic manipulator **112**. Other examples include a multi-axis machine with a spindle and rotary table, akin to a computer-numerical-control (CNC) mill, a gantry, combinations thereof, and the like. The robotic arm **404** is configured to retrieve a scanner **406** from the scanner holder **402** based on instructions corresponding to a user input or one or more parameters associated with, for example, data of a patient (e.g., patient profile, parameters of the patient's previous examination(s), etc.).

[0049] In the illustrated example, the scanner holder **402** is in the shape of a tray and includes multiple rows (e.g., three rows) for holding scanners **406**. The scanners **406** are examples of the scanners **116** in FIG. **1**. In embodiments, the different positions (e.g., rows) of the scanner holder **402** can hold different types of scanners **406**. For instance, a first row **408-1** can hold musculoskeletal (MSK) scanners, a second row **408-2** can hold high-frequency scanners (e.g., that operate above 20 megahertz (MHz)), and a third row **408-3** can hold cardiac scanners. The scanner holder **402** can include any suitable number of rows and/or columns and can hold or secure the scanners **406** in any suitable arrangement. Although the scanners **406** are illustrated as resting in an upright orientation relative to the scanner holder **402** (e.g., with a longitudinal axis **410** of the scanner **406** being orthogonal to the top surface of the scanner holder **402**, and with the rear end of the scanner **406** coupled with the scanner holder **402**), the scanner **406** can be coupled to the scanner holder **402** in any suitable way. For example, the scanners **406** can be positioned in a prostrate position relative to the top surface of the scanner holder **402** (e.g., placed with the longitudinal axis **410** of the scanner **406** parallel to the top surface of the scanner holder **402**).

[0050] FIG. **5** illustrates an example implementation **500** of another scanner holder **502**, which is part of the ultrasound system **100** from FIG. **1**. The scanner holder **502** is an example of the scanner holder **114** in FIG. **1**. In this example, the scanner holder **502** includes a plurality of couplers **504** (e.g., hooks, pegs, cantilevers, etc.) that secure or hold scanners **506** (e.g., scanners **116**), using a biasing force against the scanner **506** or holding the scanners **506** at a narrow section (e.g., neck **508**) to support the scanner **506** against gravity. The couplers **504** can be mounted to a surface, such as a wall or other substantially vertical object. In some examples, the couplers **504** can be attached to an overhanging surface. These examples can enable the robotic arm **404** to couple to the rear end (e.g., end **510**) of the scanner **506**, which is the end opposite the transducer of the scanner **506**. By coupling to the rear end of the scanner **506**, the robotic arm **404** can hold the scanner **506** such that the transducer is directed away from the robotic arm **404** and toward the patient.

[0051] FIG. **6** illustrates an example implementation **600** of another scanner holder **602**, which is part of the ultrasound system **100** from FIG. **1**. The scanner holder **602** is an example of the scanner holder **114** in FIG. **1**. The scanner holder **602** can be an automatic tool changer (ATC). For example, the scanner holder **602** is a tool magazine in the shape of a disc, which can hold multiple scanners **604**. The scanner **604** can be inserted into a protective holder **606**, and the protective holder **606** can be inserted into a slot **608** of the scanner holder **602** (or the scanner holder **402**). In embodiments, the scanners **604** and the robotic manipulator **112** are implemented with an ATC protocol that defines how the scanners **604** are maintained by the scanner holders **402** and **602** and used by the robotic manipulator **112** for scanning.

[0052] The scanner holder **602** can be integrated with the robotic manipulator **112**. In one example, the scanner holder **602** is coupled to a distal end of the robotic manipulator **112** (e.g., "neck" of robotic manipulator **112**, which is opposite a base end coupled to the ultrasound system **100**) for selecting a scanner and operating the selected scanner for scanning. For example, the robotic manipulator **112** can rotate the scanner holder **602** about a central axis **610** of the scanner holder **602** to switch between scanners **604** in the scanner holder **602** and align one of the scanners **604** with a particular position usable to couple the scanner **604** to circuitry (e.g., circuitry **612**) of the robotic manipulator **112** for providing power to the scanner **604** and for operating the scanner **604**. The other scanners **604** that are secured in the scanner holder **602** can remain in their respective slots **608**. In some aspects, instead of or in addition to holding multiple scanners **604**, the scanner holder **602** can hold multiple transducer arrays or scan heads in the protective holders **606** and/or the slots **608**. The multiple transducer arrays or scan heads can be interchangeable with a body of one of the scanners **604**, and the robotic manipulator **112** can rotate the scanner holder **602** about the central axis **610** to switch between the transducer arrays or scan heads and align one of the transducer arrays or scan heads with the body of the scanner **604** for operation.

[0053] FIG. **7** illustrates an example implementation **700** of a user interface **702** (e.g., graphical user interface), which is part of the ultrasound system **100** of FIG. **1**. The user interface **702** can be displayed via a display device **704** associated with and/or communicably coupled to the ultrasound system **100**. In aspects, the ultrasound system **100** includes the display device **704**. For instance, the display device can be included as part of ultrasound system or the ultrasound scanner **116**.

[0054] The ultrasound system **100** can display a previously captured image (e.g., 3D rendering, a 3D computer model, a 3D image) of the patient anatomy as an overlay via the user interface **702**. Under the overlay, the ultrasound system **100** can display a real-time image of the patient anatomy. Such display can enable the patient to move their anatomy to try to match the previously captured image, which represents the position of the patient anatomy in the previous ultrasound examination. Alternatively, the previously captured image can be displayed as a background layer and the real-time image can be rendered over (in front of) the previously captured image.

[0055] In an example, the patient can place their hand within the vessel **202** and the actuators and/or sensors **210** coupled or affixed to the vessel **202** can detect the position and orientation of the hand relative to the vessel **202**. The detected position and orientation of the hand is used to generate a real-time image **706** of the hand via the user interface **702**. The ultrasound system **100** also displays a previous image **708** or model of the patient's hand captured during a previous ultrasound examination and stored in the database **130**, where the previous image **708** is overlaid over (or layered under) the real-time image **706**. In one example, the previous image **708** is displayed as a faded or semi-transparent image. The patient can then adjust the position of their hand to try to match the stored image **706**.

[0056] In some implementations, the ultrasound system **100** can calculate a degree of matching between the 3D position and orientation of the hand in the previous image **708** versus the 3D position and orientation of the hand in the real-time image **706**. In aspects, the degree of matching is determined by a neural network (e.g., machine-learning model). The degree of matching can be compared to a threshold value, which indicates whether the position and orientation of the hand in the real-time image **706** is acceptable to perform the ultrasound examination. In addition, instructions can be provided to the patient to guide the patient in moving their anatomy toward matching the position and orientation of the anatomy in the previous image **708** (e.g., “Move palm downward,” “Twist wrist clockwise,” “Straighten index finger,” etc.). In an example, the user interface **702** can display written instructions and/or one or more speakers of the ultrasound system **100** can output audio instructions. A visual and/or audible indication can be provided as the degree of matching crosses the threshold. For example, the user interface **702** can change colors or brightness, the previous image **708** can change colors or disappear, etc.

[0057] In some implementations, the position of the patient anatomy relative to the vessel can differ from the previous position used in the previous examination by a degree of rotation about an axis (e.g., the x-axis). Some rotation of the patient anatomy can be accounted for in the movement instructions generated and provided to the robotic manipulator **112** to facilitate a repeatable ultrasound. For example, the movement instructions can cause the robotic manipulator **112** to adjust the orientation (e.g., rotation about an axis) or position (e.g., translational movement along an axis) of the ultrasound scanner **116-1** relative to the current position of the patient anatomy to perform the ultrasound scan of the patient anatomy according to the ultrasound protocols (e.g., angle, depth, gain, etc.) used in the previous examination. Such movement instructions enable the patient anatomy to be scanned in substantially the same manner as the previous examination, resulting in ultrasound data and images that can be compared to one another for diagnostic and procedural purposes, such as identifying inflammation, erosion, or other changes to the patient anatomy.

[0058] In an example, the real-time image **706** and the previous image **708** can be displayed in combination with the anatomy fixture **124**. In some cases, the anatomy fixture **124** is the 3D digital model of the patient anatomy.

[0059] Other information can also be presented via the user interface **702**. For example, the information can include steps on how to generate the fixture, steps being performed to generate the fixture, a completion status of the anatomy fixture, etc. A 3D rendering of the patient anatomy can be presented via the user interface **702**. In some implementations, the operator may provide input to rotate the 3D rendering about an axis or move the 3D rendering along an axis. The user input can also slice the 3D rendering along a plane or datum to view the 3D rendering of the patient anatomy along the slice.

Example Methods

[0060] FIGS. **8-11** depict methods **800**, **900**, **1000**, and **1100**, respectively for repeatable ultrasound. The methods **800**, **900**, **1000**, and **1100** are shown as a set of blocks that specify operations performed but are not necessarily limited to the order or combinations shown for performing the operations by the respective blocks. Further, any of one or more of the operations can be repeated, combined, reorganized, or linked to provide a wide array of additional and/or alternate methods. In portions of the following discussion, reference can be made to the example system **100** of FIG. **1** or to entities or processes as detailed in FIGS. **2-7**, reference to which is made for example only. The techniques are not limited to performance by one entity or multiple entities operating on one device.

[0061] FIG. **8** depicts a method **800** for repeatable ultrasound, in accordance with one or more implementations. The method **800** can be performed by the ultrasound system **100**. At **802**, a position and orientation of a patient anatomy are determined. For example, the adaptive-registration system **200** can use the one or more sensors **210** to detect the position and orientation of the patient anatomy relative to the sensors **210**, the vessel **202**, the anatomy fixture **124**, or the scanner **116**.

[0062] At **804**, registration data is generated based on the determined position and orientation of the patient anatomy. For example, the fixture generator **104** can generate the anatomy-registration data **126** corresponding to a detected position and orientation of the patient anatomy **120** in the vessel **102**. Further, the fixture generator **104** can provide the anatomy-registration data **126** to the position controller **108** to direct movement and operation of the robotic manipulator **112**.

[0063] At **806**, scan instructions are generated for a robotic manipulator coupled to an ultrasound scanner to control positioning, movement, and operation of the ultrasound scanner. For example, the processor system **110** generates the scan instructions **142** for the robotic manipulator **112** to control positioning, movement, and operation of the ultrasound scanner **116-1**. The scan instructions can include instructions to select and retrieve a scanner from a plurality of scanners from a scanner holder based on the patient anatomy and move the selected scanner according to the movement instructions from an adaptive-registration system.

[0064] At **808**, the robotic manipulator is adjusted, based on the scan instructions, to orient the ultrasound scanner based on the determined position and orientation of the patient anatomy. For example, the scan instructions **142** can include the movement instructions **136** for moving, or adjusting a position of, the robotic manipulator **112** in order to move the ultrasound scanner **116-1**. The movement instructions **136** can be based on the anatomy-registration data **126** and configured to direct the robotic manipulator to move in a manner that enables the ultrasound scanner **116-1** to generate ultrasound data. The scanner-configuration data **140** can also be generated to indicate position data of the ultrasound scanner relative to the patient anatomy or a coordinate system (3D coordinate system, 4D coordinate system, etc.).

[0065] At **810**, the ultrasound scanner is caused, based on the scan instructions, to transmit ultrasound signals at the patient anatomy. For example, the scan instructions **142** can cause the robotic manipulator **112** to initiate the ultrasound scanner **116-1** to transmit the ultrasound signals **122** at the patient anatomy **120**.

[0066] At **812**, ultrasound data is generated based on received reflections of the ultrasound signals transmitted by the ultrasound scanner at the patient anatomy. For example, processor system **110** receives the scan data **138** from the ultrasound scanner **116**. The processor system **110** can then generate ultrasound data corresponding to the scan data **138**.

[0067] At **814**, data corresponding to the ultrasound data and the registration data is stored. For example, the database **130** can store data associated with the ultrasound data and the anatomy-registration data **126**. The stored data can include images, the scan data **138**, the ultrasound data, the anatomy-registration data **126**, the scanner-configuration data **140**, the registration data **128**, etc. In aspects, the registration data is image-based, sensor-based, or both.

[0068] FIG. **9** depicts a method **900** for repeatable ultrasound, in accordance with one or more implementations. The method **900** can be performed by the ultrasound system **100**. At **902**, a vessel having an interior volume and one or more sensors is provided. The vessel can be vessel **102** and can be any suitable container in which the patient can place their anatomy. In some aspects, the vessel holds or contains the coupling agent **118** in the interior volume.

[0069] At **904**, exterior boundaries of a patient anatomy located within the interior volume of the vessel are detected via one or more sensors. For example, the sensors **210** can detect the location of the outer edges of the patient anatomy relative to the vessel **202**.

[0070] At **906**, a spatial relation of the patient anatomy relative to the vessel is determined via the one or more sensors. In addition to detecting the exterior boundaries of the patient anatomy, the sensors also determine the spatial relation of the patient anatomy relative to the vessel. The spatial relation includes the 3D position and orientation of the patient anatomy relative to the vessel.

[0071] At **908**, anatomy-registration data corresponding to the patient anatomy, the spatial relation of the patient anatomy relative to the vessel, and the exterior boundaries of the patient anatomy is determined. The ultrasound system **100** determines, for example, the anatomy-registration data **126** based on the sensor information related to the patient anatomy **120**.

[0072] At **910**, movement instructions are determined for a robotic manipulator based on the anatomy-registration data. For example, the ultrasound system **100** determines movement instructions for moving and operating the robotic manipulator **112** in a manner that avoids colliding with the patient anatomy **120**.

[0073] At **912**, the movement instructions are provided to the robotic manipulator to move and operate an ultrasound scanner for scanning the patient anatomy. For example, the ultrasound system **100** provides the movement instructions **136** to the robotic manipulator **112** to cause the robotic manipulator **112** to move and operate the ultrasound scanner **116** for scanning the patient anatomy **120**.

[0074] FIG. **10** depicts a method **1000** for repeatable ultrasound, in accordance with one or more implementations. The method **1000** can be performed by the ultrasound system **100**. At **1002**, a memory storage device is searched for stored ultrasound protocol associated with a previous ultrasound examination of a patient anatomy (e.g., associated with settings and operation of the ultrasound system, including the scanner-configuration data **140**, during the ultrasound examination). For example, the database **130** can be searched to access and retrieve registration data **128** and scan instructions **142** that were used during a previous ultrasound examination of the patient anatomy **120**. This same ultrasound protocol can be used to repeat the ultrasound examination to provide new ultrasound data that is comparable to previous ultrasound data generated during the previous examination.

[0075] At **1004**, an indication of a previous position and orientation of the patient anatomy in the previous ultrasound examination is provided based on the stored ultrasound protocol. For example, a 3D rendering of the patient anatomy in the previous orientation can be displayed via the user interface **702** of the display device **704**. The user interface **702** can provide a visual reference of the positioning of the patient anatomy for the patient to try to mimic in the present ultrasound examination. In another example, the anatomy-capture device **302** includes actuators that move and position the array of pins **304** to generate a negative (e.g., impression or imprint) of at least a portion of the patient anatomy, where the negative corresponds to the previous position and orientation of the patient anatomy.

[0076] At **1006**, instructions are provided to a patient to orient the patient anatomy to match the previous orientation. For example, instructions can be displayed via the user interface **702** and/or output via an audio output device (e.g., speaker) to guide the patient to match the current position and/or orientation of their anatomy to the previous position and orientation used in the previous ultrasound examination.

[0077] At **1008**, a current position and orientation of the patient anatomy is detected. For example, the adaptive-registration system **200** (e.g., using the one or more sensors **210**) can detect the current position and orientation of the patient anatomy in the vessel **202**. In some aspects, the adaptive-registration system **200** can include one or more patient-worn components (e.g., **204**, **206**, **208**) having one or more sensors or actuators that are in communication with the one or more sensors **210** coupled to the vessel **202**. Further, the adaptive-registration system **200** can be configured to generate the registration data with a spatial relation of the patient anatomy **120** with respect to the vessel **202** based on positions of the patient-worn components as detected by the one or more sensors **210** coupled to the vessel.

[0078] At **1010**, a degree of matching between the current orientation and the previous orientation is determined. For example, the ultrasound system **100** can quantify how closely the current position and orientation of the patient anatomy in the real-time image **706** matches the previous position and orientation of the patient anatomy in the previous image **708**. In some aspects, a neural network is used to determine the degree of matching between the determined position and orientation of the patient anatomy and the previous position and orientation of the patient anatomy from the previous ultrasound examination.

[0079] At **1012**, the ultrasound system determines if the degree of matching exceeds a threshold matching value. If the current position and orientation substantially matches the previous position and orientation (e.g., by 90% or more), then the current position and orientation can be suitable for repeatable ultrasound. If the current position and orientation are too different from the previous position and orientation, then the ultrasound data generated from the current ultrasound examination can be difficult to compare with the previous ultrasound data for purposes of identifying or diagnosing advances in a medical condition such as rheumatoid arthritis.

[0080] If the degree of matching does not exceed the threshold matching value (e.g., “NO” at **1012**), then optionally at **1014**, instructions are provided to the patient to adjust (e.g., reorient) the current position and orientation of the patient anatomy to increase the degree of matching between the current position and orientation and the previous position and orientation. The instructions can be visible instructions displayed via the user interface **702** and/or audio instructions output via a speaker.

[0081] Then, the method **1000** returns to **1008** to detect a new (e.g., adjusted) current position and orientation of the patient anatomy. For example, after the patient moves their anatomy, the method **1000** detects the new current position and orientation of the patient anatomy and recalculates the degree of matching according to the new current position and orientation. These steps can be performed in real time as the patient continues to move their anatomy to try to match the previous position and orientation.

[0082] If at **1012**, the degree of matching exceeds the threshold matching value (e.g., “YES” at **1012**), then the method **1000** proceeds to FIG. **9** (e.g., at **904**) to utilize a robotic manipulator to perform an ultrasound scan of the patient anatomy in the current position and orientation. For example, when the patient succeeds in substantially matching the current (or new current) position and orientation to the previous position and orientation (e.g., by a 90% or more match), the ultrasound system **100** can initiate the ultrasound examination by determining movement instructions **136** for the robotic manipulator **112** to use for holding and operating the ultrasound scanner **116** in a way to repeat the previous ultrasound examination (e.g., by scanning the patient anatomy according to the same ultrasound protocol used in the previous ultrasound examination).

[0083] FIG. **11** depicts a method **1100** for generating an anatomy fixture for repeatable ultrasound, in accordance with one or more implementations. The method **1100** can be performed by the ultrasound system **100**. At **1102**, a vessel having an interior volume is provided. The vessel can be vessel **102** and can be any suitable container in which the patient can place their anatomy. In some aspects, the vessel **102** holds or contains the coupling agent **118** in the interior volume. In an example, the vessel is provided during a first ultrasound examination of the patient anatomy **120**.

The coupling agent **118** can conform to the patient anatomy **120** and act as a conductor that facilitates transmission of the ultrasound signals **122** between the ultrasound scanner **116-1** and the patient anatomy **120**.

[0084] At **1104**, one or more characteristics of a patient anatomy located within the vessel are detected. For example, the anatomy-capture device **106** can capture or detect characteristics such as shape, position, orientation, and/or exterior boundaries (e.g., contour) of the patient anatomy, as disclosed herein. In aspects, the one or more characteristics are captured by the anatomy fixture **124**, which can be formed from a shape-adapting material, a shape-adapting mechanism (e.g., anatomy-capture device **302** with the array of pins **304**), or a three-dimensional computer model. The one or more characteristic can be captured by the adaptive-registration system **200** having the one or more sensors **210** coupled to the vessel **202**, which are configured to detect the position and orientation of the patient anatomy **120** located within the vessel **202** and generate corresponding sensor data.

[0085] At **1106**, a negative 3D shape of the patient anatomy is determined based on the one or more detected characteristics. The characteristics can be used to determine, for example, data usable to create a mold configured to support the patient anatomy. The negative 3D shape of the patient anatomy can be determined using, for example, the array of pins **304**, where each pin in the array of pins **304** has a central axis and is displaceable along the central axis, and a plurality of sensors configured to detect a depth and location of each pin of the array of pins **304** as the patient anatomy **120** displaces a subset of the pins **304**. The depth and location of each pins can be recorded as the registration data to represent a negative of a contour of an exterior surface of a portion of the patient anatomy **120**. In some implementations, the anatomy fixture **124** includes a plurality of actuators, where one or more of the actuators is configured to, at a subsequent time, displace at least some of the pins **304** of the array of pins **304** based on the registration data to generate the negative of the contour of the exterior surface of the portion of the patient anatomy **120**. In some aspects, information can be provided via the user interface **702**, where the information includes steps on how to generate the anatomy fixture, steps being performed to generate the anatomy fixture, or a completion status of the anatomy fixture.

[0086] At **1108**, an anatomy fixture is generated based on the negative 3D shape of the patient anatomy. For example, the fixture generator **104** generates the anatomy fixture **124** based on characteristics of the patient anatomy **120** that are captured by the anatomy-capture device **106**. The anatomy fixture **124** can include any suitable fixture, such as a mold, 3D computer model, a shape-adapting material, a shape-adapting mechanism, etc. In addition, the anatomy fixture can represent a negative of at least a portion of the patient anatomy **120** and can be used to support the patient anatomy **120** or provide a reference to a particular position and orientation of the patient anatomy **120** as defined in the first ultrasound examination.

[0087] The anatomy fixture defines at least a portion of the exterior boundaries (e.g., outline) of the patient anatomy. These defined boundaries combined with the characteristics (e.g., shape, size, etc.) provide an indication of a remaining portion of the exterior boundaries of the patient anatomy that are not defined by the anatomy fixture alone. For example, the array of pins **304** of the anatomy fixture **124** can define the contour of approximately half of a patient's hand (e.g., palm-side of hand facing the anatomy fixture) but the surface of the back of the hand is not defined by the anatomy fixture **124**. In this case, the data including the detected shape, size, etc. of the hand can be combined with the anatomy fixture **124** to define the location of the surface of the back of the hand relative to the anatomy fixture itself. Such information can be used, for example, to avoid causing the ultrasound scanner **116** to collide with the back of the patient's hand.

[0088] At **1110**, at a subsequent time (e.g., during a subsequent ultrasound examination), the anatomy fixture is provided to support the patient anatomy in a same position and orientation as defined by the one or more detected characteristics of the patient anatomy detected in the first ultrasound examination. The anatomy fixture **124** can support the patient anatomy **120** in the same position and orientation across multiple serial ultrasound examinations. The placement of the anatomy fixture in the vessel **102** can define the spatial relation (e.g., position and orientation) of the patient anatomy **120** relative to the vessel **102**. The method **1100** can then proceed to FIG. **9** (e.g., at **904**) to utilize the robotic manipulator **112** to perform an ultrasound scan of the patient anatomy **120**.

Example Models and Devices

[0089] As described, many of the features described herein can be implemented using a machine-learned model. For the purposes of this disclosure, a machine-learned model is any model that accepts an input, analyzes, and/or processes the input based on an algorithm derived via machine-learning training, and provides an output. A machine-learned model can be conceptualized as a mathematical function of the following form:

$$f(\hat{s},\theta)=\hat{y} \qquad \text{Equation (1)}$$

[0090] In Equation (1), the operator f represents the processing of the machine-learned model based on an input and providing an output. The term s represents a model input, such as ultrasound data. The model analyzes/processes the input s using parameters θ to generate output ŷ (e.g., the anatomy-registration data **126**, degree of matching between positions and orientations of a patient anatomy in current and previous ultrasound examinations, etc.). Both ŝ and ŷ can be scalar values, matrices, vectors, or mathematical representations of phenomena such as categories, classifications, image characteristics, the images themselves, text, labels, or the like. The parameters θ can be any suitable mathematical operations, including but not limited to applications of weights and biases, filter coefficients, summations or other aggregations of data inputs, distribution parameters such as mean and variance in a Gaussian distribution, linear-algebra-based operators, or other parameters, including combinations of different parameters, suitable to map data to the desired output.

[0091] FIG. **12** represents an example machine-learning architecture **1200** used to train a machine-learned model M **1202**, which can be used to implement at least some of the techniques disclosed herein. An input module **1204** accepts an input ŝ **1206**, which can be an array with members ŝ.sub.1 through ŝ.sub.n. The input ŝ **1206** is fed into a training module **1208**, which processes the input ŝ **1206** based on the machine-learning architecture **1200**. For example, if the machine-learning architecture **1200** uses a multilayer perceptron (MLP) model **1210**, the training module **1208** applies weights and biases to the input ŝ **1206** through one or more layers of perceptrons, each perceptron performing a fit using its own weights and biases according to its given functional form. MLP weights and biases can be adjusted so that they are optimized against a least mean square, logcosh, or other optimization function (e.g., loss function) known in the art. Although an MLP model **1210** is described here as an example, any suitable machine-learning technique can be employed, some examples of which include but are not limited to k-means clustering **1212**, convolutional neural networks (CNN) **1214**, a Boltzmann machine **1216**, Gaussian mixture models (GMM), and long short-term memory (LSTM). The training module **1208** provides an input to an output module **1218**. The output module **1218** analyzes the input from the training module **1208** and provides a prediction output in the form of ŷ **1220**, which can be an array with members ŷ.sub.1 through ŷ.sub.m. The prediction output **1220** can represent a known correlation with the input ŝ **1206**, such as, for example, anatomy information (e.g., characteristics of the patient anatomy **120**).

[0092] In some examples, the input ŝ **1206** can be training input labeled with known output correlation values, and these known values can be used to optimize the output ŷ **1220** in training against the optimization/loss function. In other examples, the machine-learning architecture **1200** can categorize the output ŷ **1220** values without being given known correlation values to the inputs ŝ **1206**. In some examples, the machine-learning architecture **1200** can be a combination of machine-learning architectures. By way of example, a first network can use input ŝ **1206** and provide prediction output ŷ **1220** as an input ŝ.sub.ML to a second machine-learned architecture, with the second machine-learning architecture providing a final prediction output ŷ.sub.f. In another example, one or more machine-learning architectures can be implemented at various points throughout the training module **1208**.

[0093] In some ML models, all layers of the model are fully connected. For example, all perceptrons in an MLP model act on every member of s. For an MLP model with a 100×100 pixel image as the input, each perceptron provides weights/biases for 10,000 inputs. With a large, densely layered model, this can result in slower processing and/or issues with vanishing and/or exploding gradients. A CNN, which may not be a fully connected model, can process the same image using 5×5 tiled regions, requiring only 25 perceptrons with shared weights, giving much greater efficiency than the fully connected MLP model.

[0094] FIG. **13** represents an example model **1300** using a CNN to process an input image **1302**, which includes representations of objects that can be identified via object recognition, such as people or cars. Although this example includes people and cars as general objects in the input image **1302**, the input image **1302** can include the ultrasound image **132**, as described above, having representations of anatomy, such as bodily structures. Convolution A **1304** can be performed to create a first set of feature maps (e.g., feature maps A **1306**). A feature map can be a mapping of aspects of the input image **1302** given by a filter element of the CNN. This process can be repeated using feature maps A **1306** to generate further feature maps B **1308**, feature maps C **1310**, and feature maps D **1312** using convolution B **1314**, convolution C **1316**, and convolution D **1318**, respectively. In this example, feature maps D **1312** become the input for fully connected network layers **1320**. In this way, the ML model can be trained to recognize certain elements of the image, such as people or cars, and provide an output **1322** that, for example, identifies the recognized elements.

[0095] Although the example of FIG. **13** shows a CNN as a part of a fully connected network, other architectures are possible and this example should not be seen as limiting. There can be more or fewer layers in the CNN. A CNN component for a model can be placed in a different order, or the model can contain additional components or models. There may be no fully connected components, such as a fully convolutional network. Additional aspects of the CNN, such as pooling, downsampling, upsampling, or other aspects known to people skilled in the art can also be employed.

[0096] FIG. **14** illustrates a block diagram of an example computing device **1400** that can perform one or more of the operations described herein, in accordance with some implementations. The computing device **1400** can be connected to other computing devices in a local area network (LAN), an intranet, an extranet, and/or the Internet. The computing device can operate in the capacity of a server machine in a client-server network environment or in the capacity of a client in a peer-to-peer network environment. The computing device can be provided by a personal computer (PC), a server computer, a desktop computer, a laptop computer, a tablet computer, a smartphone, or any machine capable of executing a set of instructions (sequential or otherwise) that specify actions to be taken by that machine. Further, while only a single computing device is illustrated, the term “computing device” shall also be taken to include any collection of computing devices that individually or jointly execute a set (or multiple sets) of instructions to perform the methods discussed herein. In some implementations, the computing device **1400** is one or more of an ultrasound machine, an access point, and a packet-forwarding component.

[0097] The example computing device **1400** can include a processing device **1402** (a general-purpose processor, a programmable logic device (PLD), etc.), a main memory **1404** (e.g., synchronous dynamic random-access memory (DRAM), read-only memory (ROM)), and a static memory **1406** (e.g., flash memory and a data storage device **1408**), which can communicate with each other via a bus **1410**. The processing device **1402** can be provided by one or more general-purpose processing devices such as a microprocessor, a central processing unit, or the like. In an illustrative example, the processing device **1402** comprises a complex instruction set computing

(CISC) microprocessor, a reduced instruction set computing (RISC) microprocessor, a very long instruction word (VLIW) microprocessor, or a processor implementing other instruction sets or processors implementing a combination of instruction sets. The processing device **1402** can also comprise one or more special-purpose processing devices such as an application-specific integrated circuit (ASIC), a field programmable gate array (FPGA), a digital signal processor (DSP), a network processor, or the like. The processing device **1402** can be configured to execute the operations described herein, in accordance with one or more aspects of the present disclosure, for performing the operations and steps discussed herein.

[0098] The computing device **1400** can further include a network interface device **1412**, which can communicate with a network **1414**. The computing device **1400** also can include a video display unit **1416** (e.g., a liquid crystal display (LCD), organic light-emitting diode (OLED), or a cathode ray tube (CRT)), an alphanumeric input device **1418** (e.g., a keyboard), a cursor control device **1420** (e.g., a mouse), and an acoustic signal generation device **1422** (e.g., a speaker and/or a microphone). In one embodiment, the video display unit **1416**, the alphanumeric input device **1418**, and the cursor control device **1420** can be combined into a single component or device (e.g., an LCD touch screen).

[0099] The data storage device **1408** can include a computer-readable storage medium **1424** on which can be stored one or more sets of instructions **1426** (e.g., instructions for carrying out the operations described herein, in accordance with one or more aspects of the present disclosure). The instructions **1426** can also reside, completely or at least partially, within the main memory **1404** and/or within the processing device **1402** during execution thereof by the computing device **1400**, where the main memory **1404** and the processing device **1402** also constitute computer-readable media. The instructions can further be transmitted or received over the network **1414** via the network interface device **1412**.

[0100] Various techniques are described in the general context of software, hardware elements, or program modules. Generally, such modules include routines, programs, objects, elements, components, data structures, and so forth that perform particular tasks or implement particular abstract data types. The terms “module,” “functionality,” and “component” as used herein generally represent software, firmware, hardware, or a combination thereof. In some aspects, modules described herein (e.g., the position controller **108**, fixture generator **104**, etc.) are embodied in the data storage device **1408** of the computing device **1400** as executable instructions or code. Although represented as software implementations, the described modules can be implemented as any form of a control application, software application, signal-processing and control module, hardware, or firmware installed on the computing device **1400**.

[0101] While the computer-readable storage medium **1424** is shown in an illustrative example to be a single medium, the term “computer-readable storage medium” should be taken to include a single medium or multiple media (e.g., a centralized or distributed database and/or associated caches and servers) that store the one or more sets of instructions. The term “computer-readable storage medium” shall also be taken to include any medium that is capable of storing, encoding, or carrying a set of instructions for execution by the machine and that causes the machine to perform the methods described herein. The term “computer-readable storage medium” shall accordingly be taken to include, but not be limited to, solid-state memories, optical media, and magnetic media.

CONCLUSION

[0102] Embodiments for repeatable ultrasound are disclosed. The repeatable ultrasound techniques disclosed herein provide solutions that enable generation of consistent ultrasound images suitable for the early detection and management of one or more medical conditions, including rheumatoid arthritis. These techniques reduce and/or remove the dependency of the operator and the inconsistencies resulting from patient movement, so that the ultrasound system can generate matching image views needed in serial ultrasound examinations for the assessment and treatment of such medical conditions.

Claims

1. An ultrasound system comprising: an ultrasound scanner configured to generate ultrasound data based on received reflections of ultrasound signals transmitted by the ultrasound scanner at a patient anatomy; a robotic manipulator configured to couple to the ultrasound scanner, the robotic manipulator configured to control positioning, movement, and operation of the ultrasound scanner; a processor system configured to generate scan instructions for the robotic manipulator and receive the ultrasound data from the ultrasound scanner; an adaptive-registration system configured to determine a position and orientation of the patient anatomy and adjust the robotic manipulator to orient the ultrasound scanner based on the determined position and orientation of the patient anatomy; and a database configured to store data corresponding to the ultrasound data and anatomy-registration data associated with the determined position and orientation of the patient anatomy.
2. The ultrasound system of claim 1, further comprising a scanner holder configured to hold a plurality of ultrasound scanners, and wherein the robotic manipulator is configured to: select a scanner from the plurality of ultrasound scanners from the scanner holder based on the patient anatomy; retrieve the selected scanner from the scanner holder; and move the selected scanner according to movement instructions from the adaptive-registration system, wherein the selected scanner is the ultrasound scanner.
3. The ultrasound system of claim 1, further comprising a position controller configured to generate movement instructions for the robotic manipulator based on the anatomy-registration data, wherein the movement instructions are configured to direct the robotic manipulator to move in a manner that enables the ultrasound scanner to generate the ultrasound data.
4. The ultrasound system of claim 3, wherein the position controller is configured to generate scanner-configuration data for indicating position data of the ultrasound scanner relative to the patient anatomy or a three-dimensional coordinate system.
5. The ultrasound system of claim 1, wherein the registration data is image-based registration data.
6. The ultrasound system of claim 1, wherein the registration data is sensor-based registration data.
7. The ultrasound system of claim 1, wherein the adaptive-registration system includes: an anatomy-capture device configured to capture characteristics of the patient anatomy; and a fixture generator configured to generate an anatomy fixture based on the captured characteristics of the patient anatomy, the anatomy fixture configured to support the patient anatomy in the determined position and orientation during an ultrasound examination.
8. The ultrasound system of claim 7, wherein the fixture generator is configured to: generate the anatomy-registration data; and provide the anatomy-registration data to a position controller configured to direct movement and operation of the robotic manipulator.
9. The ultrasound system of claim 7, wherein the anatomy fixture is formed from a shape-adapting material, a shape-adapting mechanism, or a three-dimensional computer model.
10. The ultrasound system of claim 1, further comprising: a vessel configured to contain a coupling agent that conforms to the patient anatomy and acts as a conductor that facilitates transmission of the ultrasound signals between the ultrasound scanner and the patient anatomy.
11. The ultrasound system of claim 10, wherein the adaptive-registration system includes one or more sensors coupled to the vessel, wherein the one or more sensors are configured to detect the position and orientation of the patient anatomy located within the vessel and generate corresponding sensor data.
12. The ultrasound system of claim 11, wherein the adaptive-registration system includes a fixture generator configured to: receive the sensor data from the one or more sensors; and generate an anatomy fixture that is a negative of at least a portion of the patient anatomy can support the patient anatomy in the detected position and orientation.

13. The ultrasound system of claim 12, further comprising a user interface for providing information including steps on how to generate the anatomy fixture, steps being performed to generate the anatomy fixture, or a completion status of the anatomy fixture.

14. The ultrasound system of claim 11, further comprising one or more patient-worn components having one or more sensors or actuators that are in communication with the one or more sensors coupled to the vessel, wherein the adaptive-registration system is configured to generate the registration data with a spatial relation of the patient anatomy with respect to the vessel based on positions of the patient-worn components as detected by the one or more sensors coupled to the vessel.

15. The ultrasound system of claim 1, further comprising a user interface for providing an indication of a previous position and orientation of the patient anatomy from a previous ultrasound examination, wherein: the database is configured to store ultrasound data including the previous position and orientation of the patient anatomy from the previous ultrasound examination; and the adaptive-registration system is configured to provide an indication of a degree of matching between the determined position and orientation of the patient anatomy and the previous position and orientation of the patient anatomy.

16. The ultrasound system of claim 15, wherein the adaptive-registration system utilizes a neural network to determine the degree of matching between the determined position and orientation of the patient anatomy and the previous position and orientation of the patient anatomy from the previous ultrasound examination.

17. The ultrasound system of claim 1, further comprising an anatomy fixture including: an array of pins, each pin in the array of pins having a central axis and being displaceable along the central axis; and a plurality of sensors configured to detect a depth and location of each pin of the array of pins as the patient anatomy displaces a subset of the pins, wherein the depth and location of each pin is recorded as the registration data to represent a negative of a contour of an exterior surface of a portion of the patient anatomy.

18. The ultrasound system of claim 17, wherein the anatomy fixture includes a plurality of actuators, wherein one or more actuators of the plurality of actuators is configured to, at a subsequent time, displace at least some of the pins of the array of pins based on the registration data to generate the negative of the contour of the exterior surface of the portion of the patient anatomy.

19. A method for repeatable ultrasound, the method comprising: providing a vessel having an interior volume; detecting exterior boundaries of a patient anatomy located within the interior volume of the vessel; detecting a spatial relation of the patient anatomy relative to the vessel; generating anatomy-registration data corresponding to the patient anatomy based on the spatial relation of the patient anatomy relative to the vessel and the exterior boundaries of the patient anatomy; determining movement instructions for a robotic manipulator based on the anatomy-registration data; and providing the movement instructions to the robotic manipulator to move and operate an ultrasound scanner for scanning the patient anatomy.

20. The method of claim 19, further comprising: generating an anatomy fixture based on the exterior boundaries of the patient anatomy and the spatial relation of the patient anatomy relative to the vessel; and providing the anatomy fixture to support the patient anatomy in the same position and orientation across multiple serial ultrasound examinations.
